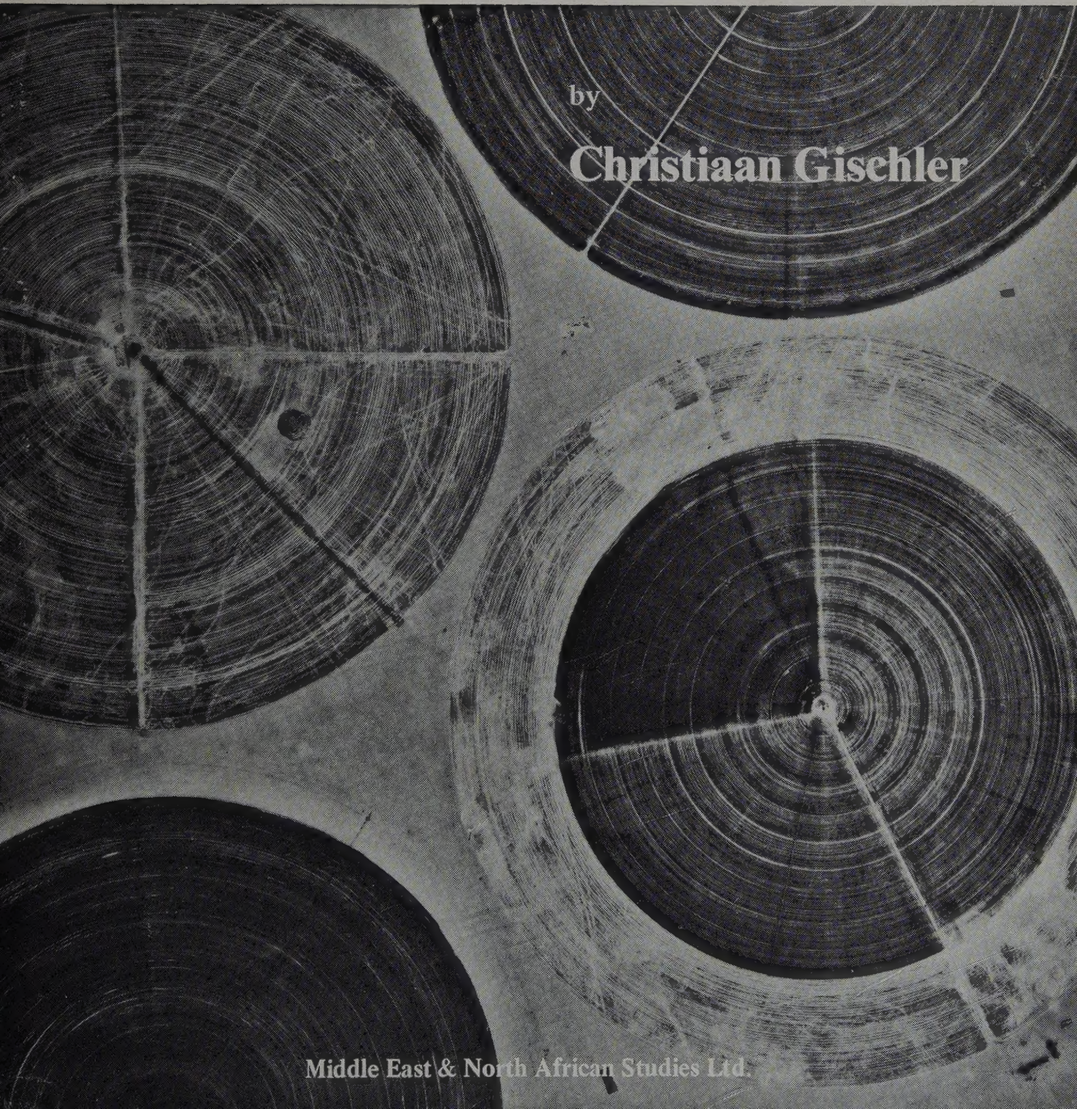
MENAS Resources Studies

Water Resources in the Arab Middle East and North Africa



by

Christiaan Gischler

Middle East & North African Studies Ltd.

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The status of surface and ground-water resources in the Middle East and North Africa is receiving greater attention as all economic development depends on these crucial but easily degraded resources. All countries of the region experience some deficiency in water resources. Some states have no significant surface flow, such as the Gulf States and Libya, while Iraq, Syria, Egypt and Sudan have limited tracts of well watered land. Elsewhere ground water resources are extensive but insufficiently researched.

The author has brought together the most comprehensive review of previously published sources, but the main value of this resource study is its reference to a large number of unpublished reports and conference papers of the past ten years. He provides an unsensational assessment of the scale of renewable and fossil water resources and draws attention to the achievements and problems in managing water in the arid and semi-arid Middle F[illegible] [illegible]nd North Africa.

The author served U[illegible] for six years where he [illegible] particularly privileged p[illegible]n to review current and developing views on water resources and their potential role in economic development.

Water Resources in the Arab Middle East and North Africa

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Dedicated to my wife and
the deserts of her country

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NOTE ON TRANSLITERATION

The place names and Arabic words have been transliterated in the form most familiar in the country to which reference is being made in the text. Thus in parts of the Middle East where an anglicized form of transliteration is common the names have generally been transliterated according to the standard system of the United States Board on Geographic Names. In North Africa where the French system is usual, then a French form of transliteration has been used.

Abbreviations

c	approximately
CI	Continental Intercalaire
EC	Electrical conductivity in mho/cm
g	gram
ha	hectare
kg	kilogram
l	litre
l/sec	litres per second
m	metre
mg	milligram
mn	million
μ	micro
μmho	micromho – measure of electrical conductivity
no.	number
ppm	parts per million. As commonly measured and used ppm is equivalent to milligrams per litre
pop.	population

Acronyms

ACSAD	Arab Centre for the Study of Arid Zones and Dry Lands
ARE	Arab Republic of Egypt
CMRE	Comité Maghrebin des Ressources en Eau
DEMRH	Direction des Etudes de Milieu et de la Recherche Hydraulique
FAO	Food and Agriculture Organization
HEP	Hydroelectric power
IAEA	International Atomic Energy Authority
IHD	International Hydrological Decade
MAB	Man and Biosphere

ROSTAS	Regional Office for Science and Technology in the Arab States
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
UNESCO	United Nations Educational Scientific and Cultural Organization

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Part I

Water Resources and
Water Resource Management

INTRODUCTION

More closely than by faith alone, the Arab states are united by their common language and their location in the most extensive arid zone of the world: the Sahara and Arabian deserts with their bordering semi-arid lands. Moulded by forced adaptation to their environment, they have been able to endure its hardship and survived in the dry areas through a flexible life system, mainly expressed in nomadism and supported by the major centres of learning. These centres were the cities along the major rivers (Cairo and Baghdad) and along the peripheral mountain ranges which receive more rainfall (Fez, Kairouan, Damascus, Aleppo, etc.) and which are known for their tremendous absorptive power. In this same context, the oases sparsely scattered all over the Sahara and Arabian deserts have provided essential support to the nomads and traders of the deserts.

When, however, the meagreness of their lands was enriched by the discovery of vast oil and gas fields located beneath the barren deserts, the Arab countries entered the age of science and technology (science being an old companion). The exploitation of this non-renewable resource provided many of the Arab countries with an unprecedented wealth which, in some cases, was even able to exceed the increasing financial and material demands generated by the demographic explosion and rises in the standard of living.

However, like everything which is exhaustible, this wealth has its limits and the problem arises of how to convert this wealth into renewable commodities within a certain time limit. This should be accomplished in such a way that the new commodities will little by little replace the vanishing oil reserves and permanently raise the standard of living of the Arab peoples from its former subsistence level to a higher and productive level which would benefit both the Arabs and the rest of the world, by making better use of large land surfaces, coast-lines, sunshine, mineral wealth and other natural resources of which the limiting factors are always the lack of fresh water, the sparse soil cover and the scattered vegetation where it exists.

In financial terms this may be expressed as: 'How to invest this reserve capital at a high interest rate'. But the interest rate should not only be guaranteed, it should also be received in 'super-hard' currency, for example in high quality water-volume units or, even better, 'lumping' water, soil and vegetation together and taking the essential sunshine for granted, in *calorie units.* In this connection it is interesting to note that recent estimates have indicated that the solar energy received by Saudi Arabia alone, in one year, is equivalent to the entire proved reserves of coal, oil and natural gas in the world.

Providence has confronted the Arab states with the challenge of making the best possible use of their combined efforts in science and technology. Much

imagination and much co-operation are required from the joint capacity of Arab science and technology in the field of environmental development to remove little by little the constraints imposed by aridity. At the same time it must be remembered that in the field of natural resources, the available technologies being applied in other parts of the world cannot be copied without reviewing them thoroughly before they can be incorporated into the production processes of the region.

Therefore, it is essential that the Arab scientists not only take notice of different trends of development in the outside world, especially in other arid zones, but also that they convert these developments, if necessary with foreign expertise, into field-tested production routines which can be applied in the natural environment without disrupting its sensitive equilibrium, and which can be assimilated by the Arab economies at all levels.

OCCURRENCE OF NATURAL WATER RESOURCES

Geographical situation

The Arab countries cover the world's most extensive arid zone: the major part of the Sahara, the Middle East and the Arabian Peninsula. They comprise the countries of Africa bordering the Atlantic Ocean north of Senegal, the countries forming the south and east coast of the Mediterranean, the countries surrounding the Red Sea and Gulf of Aden, with the exception of Ethiopia, and the countries north-west and west of the Arabian Gulf.

Sources of rainfall

The only reliable source of precipitation which supplies the area with water falls either on the marginal mountain chains and some isolated mountains in the interiors, or is brought from the south by the monsoonal air circulation system, whose influence diminishes towards the Tropic of Cancer. This precipitation varies from about 150 mm/annum to as much as 2000 mm/annum. In contrast, the desert areas in between receive less than 150 mm/annum. In fact, the average annual rainfall figure in these areas has no practical meaning as the only significant precipitation is supplied by the rare and unpredictable rain-storms which occur with a frequency of less than once a year, and which may strike any part of the total desert area. In the latter case, very occasional rainfall, although of great importance for all life in the desert, should be clearly distinguished from the reliable rainfall supply mentioned before, on which, for instance, dry farming depends.

The mountainous precipitation collectors

The mountain chains and upland areas which function as precipitation collectors, either in the form of rain or snow, are the following (see Fig. 1).

The Atlas ranges in the Maghreb, Jabal Akhdar in north-east Libya, the Egyptian Red Sea hills and their southern continuation in the Sudan and the Ethiopian Highlands, the ranges at the Arabian side of the Red Sea from South Yemen via North Yemen, Saudi Arabia inwards to Jordan and Lebanon as far as Turkey (the Lebanon and Anti-Lebanon mountain ridges and extensions to the north), the Taurus and Zagros mountains bordering the Middle East from the north and east and the other Jabal Akhdar (green mountains) at the extreme east of the Arabian Peninsula alongside the Gulf of Oman. The isolated massifs in the interior should also be mentioned namely the Middle Saharan massifs of Hoggar, Tassili, Tibesti, Ennedi and the Darfour mountains in East Sudan. These

mountains generally reach an altitude of 1000 m while the summits exceed often 2000 m and even 3000 m in some cases.

It will be clear that even dry and hot air masses being forced to rise over the mountainous areas, may be cooled off until the saturation point of the vapour pressure has been reached and precipitation results. However, all these remote mountains lie in the semi-arid areas of the region, primarily characterized by well-pronounced periods of drought between rainy seasons, at latitudes where evaporation through intensive solar radiation is high. The semi-arid mountainous precipitation collectors give rise to very limited and intermittent surface runoff, feeding the ephemeral streams and supplying the infiltration waters for the recharge of the sub-surface aquifers.

Riverflow in arid zones

River discharge depends on the height, extent and geographical location of the mountainous complex forming the head waters region of that river. As soon as the rivers have reached the wide valleys, where the aridity becomes more intense, the flow velocity drops, the river bed becomes wider and water is more liable to evaporation resulting in a gradual decrease of the river discharge. As the real evaporation losses are proportional to the water surface area, the chance of survival of a river decreases with its length. Swamps and irrigation schemes where the water surface increases and the water depth is small contribute to reduce riverflow.

There are a number of rivers in the Middle East which withstand extreme aridity for a major part of their courses, namely the Nile and the Euphrates (the Tigris river, flowing parallel to the Zagros mountains receives perennial tributaries from the east up to its mouth, and therefore should not be included in this discussion).

All other rivers fed by the Ethiopian Highlands, the Atlas and Lebanon chains, reach the sea within a limited distance. Some rivers discharge into the interior and they penetrate more or less deeply into the desert depending on the levels of, and fluctuations in, the precipitation in their respective head water regions. The following map and table show the international rivers which Arab countries share with each other or with outside countries. It also demonstrates the importance of the orographic massifs (see Fig. 1).

Recharge of aquifers in the periphery of mountains which attract orographic rainfall

The recharges of the aquifers in the zone surrounding the mountainous complexes is facilitated by their structure. The older and generally more consolidated formations outcrop at higher altitudes, through the increasing influence of erosion with height. The coarse and permeable detritus material of the aquifer formations fans out from the foot of the mountains. The fine-

grained, less permeable deposits reach their final destination in the vast intermontane depressions.

Runoff water infiltrates the permeable detritus deposits where it establishes free water table conditions. Under the influence of the impermeable covering formations, the open aquifers change into (two-dimensional) pressure conduits or artesian aquifers. It is through these aquifers that, under the influence of the hydraulic gradient, groundwater can be transported over long distances from its intake areas especially as it is well protected against evaporation.

The natural discharge of these aquifers may occur in topographic depressions in the interior where salt accumulations show the discharge of groundwaters. Examples of famous Sahara aquifers are the Continental Intercalaire of the Western Sahara and its Eastern Sahara equivalent of the Nubian Sandstone, also well known in the Arabian Peninsula, both being mainly of Cretaceous age.

An interesting variation of the general rule is illustrated by the folded mountain ridges of the Middle East, of Jurassic, Cretaceous and Palaeogene Limestone formations of the Tethys Geosyncline belt surrounding the Arabo-Nubian shield in the north and east. In the folded zones where the massive limestones became fissured, conditions for karst formation were favourable. Here precipitation infiltrates at a high altitude in the limestone aquifers, decreasing the runoff coefficient. The groundwater follows preferred paths along fissured karst zones to emerge in springs at varying distances from the intake areas. In the neighbourhood of the coastline this groundwater flow pattern can give rise to sub-marine freshwater springs. In the Middle East Karst springs of $10\,m^3$/sec and more are not exceptional.

Water and soil

As the mountainous slopes in semi-arid regions are characterized by sparse vegetation the capacity of the vegetation cover for absorbing water is naturally poor and the runoff coefficient is correspondingly high. Taking into consideration the consequent lack of a root system to retain the soil *in situ*, the soil is easily carried away by the runoff waters, cutting deep erosion gullies into the mountain slopes. Torrential water highly charged with suspended matter runs down the mountain slopes creating the degraded 'bad land' topography. As soon as there is a significant change in the slope gradient at the foot of the orographic massifs bordering the wide depressions or coastal plains where rainfall is scarce and evaporation is high, these waters drop their sediment load. In this way floods can instantaneously cover cultivated plains very rapidly with detritus deposits sometimes exceeding 1 m in depth. Adverse soil moisture conditions can also cause soil degradation. Evaporation in high water table areas results in the large-scale precipitation of salts, and the so-called 'sebkhas',* being a mixed

* A 'sebkha' is a marshy area, often surrounded by salt-resistant vegetation. The 'sebkha' accumulates silt, wind-blown sand and has a high salt content because of periodic flooding and evaporation.

Fig. 1. The Arab Middle East and Northern Africa showing the major surface water flows and the Nubian sandstone aquifer. See page 9 opposite for a list of rivers. International borders not authenticated.

Table 1. List of international rivers

No.	International river	Recharge area	Countries in downstream direction	Area drainage basin in km²
1	Senegal		Guinee, Mali, Senegal, Mauretania	
2	Atui	Atlas	Mauretania	
3	Oued Draa		Morocco, Algeria	
4	Oued Daoura		Morocco, Algeria	
5	Qued Guir		Morocco, Algeria	
6	Tafna		Morocco, Algeria	
7	Medjerda		Algeria, Tunisia	23 000
8	Nile	Central African up-lands and Sudan	Tanzania, Kenya, Burundi Rwanda, Uganda, Sudan Egypt	2 800 000
9	White Nile		Sudan	
10	Sobat	Ethiopian Highlands	Ethiopia, Sudan	
11	Blue Nile		Ethiopia, Sudan	325 000
12	Atbara		Ethiopia, Sudan	
13	Gash		Ethiopia, Sudan	21 000
14	Baraka		Ethiopia, Sudan	
15	Lagh Bor		Ethiopia, Kenya, Somalia	
16	Juba		Ethiopia, Somalia	200 000
17	Scebeli		Ethiopia, Somalia	260 000
18	Yarmouk		Syria, Jordan	
19	Nahr el Assi (Orontes)		Lebanon, Syria	
20	Euphrates	Taurus/ Zagros	Turkey, Syria, Iraq	350 000
21	Khabur		Turkey, Syria	31 800
22	Tigris		Turkey, Syria, Iraq	253 000 (Iraq only)
23	Great Zab		Turkey, Iraq	26 473
24	Karun		Iran, Iraq	

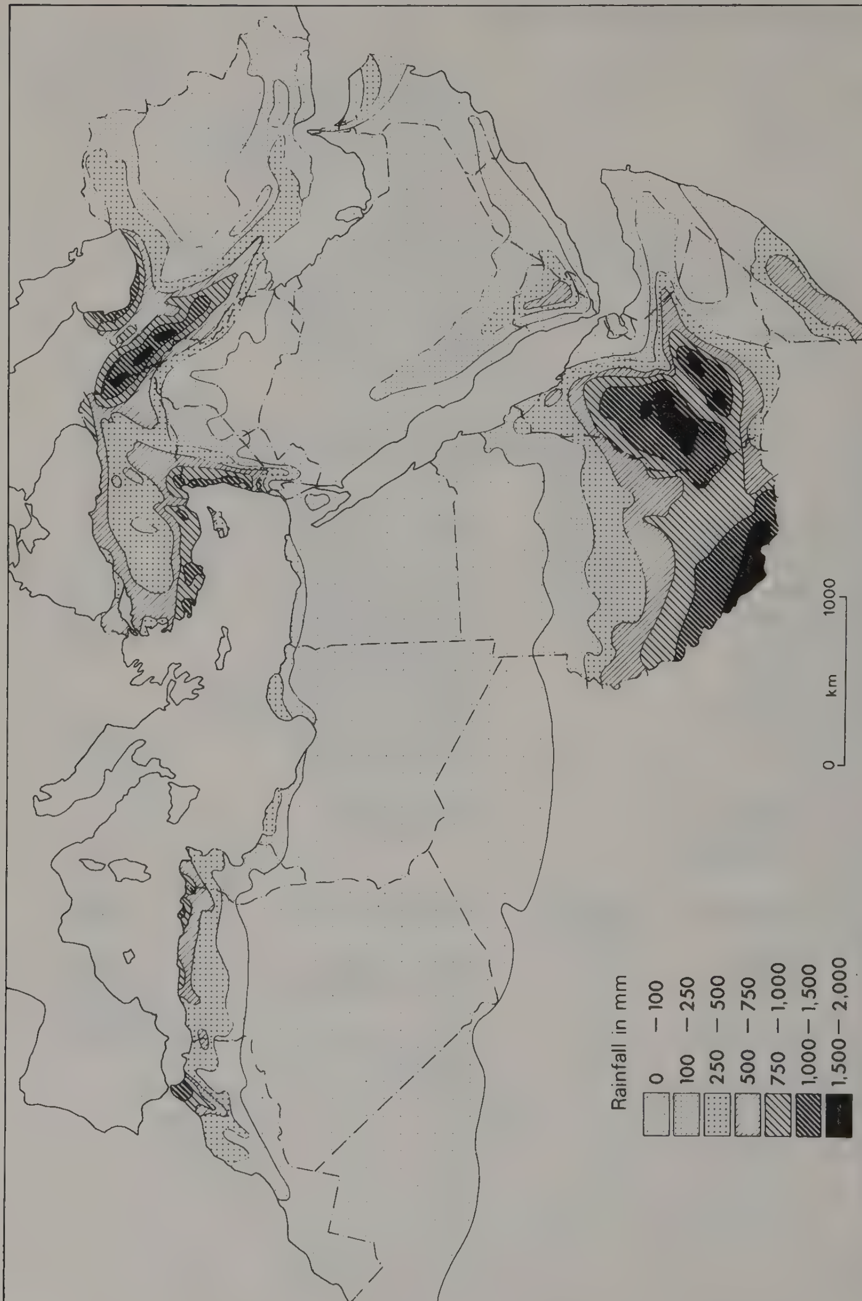

Fig. 2. Rainfall in the Middle East and North Africa.

deposit of salt and clay, originate as characteristic coastal formations in the arid zones.

Renewable and non-renewable water resources

All rivers of perennial and intermittent character as well as their alluvial valley infills, supply renewable water resources. Aquifers also supply this type of water in areas where groundwater withdrawals of long duration do not cause a lowering of the water table or pressure level. However, if large-scale withdrawals in remote areas far from intake regions will continuously lower the water table or related piezometric surface, the aquifers are considered to be non-renewable. In this situation recharge cannot compensate for the local water withdrawal and consequently water is mined. Famous examples of over-exploitation or mining of groundwater are Kufrah in Libya and the New Valley in Egypt. In both cases water withdrawals were from the Nubian Sandstone aquifers, but many similar cases occur in the western Sahara and the Arabian Peninsula.

Exploitation of renewable resources is normally justified, but withdrawal of so-called fossil groundwater needs extensive economic appraisal, taking into account the amortization period of investments against the estimated expoiltable water reserves and the expected gains resulting from the exploitation of the fossil natural resource. As a large-scale water supply in desert areas may stimulate either the settlement of a nomadic population or the migration of the necessary labour force from remote population centres, imposing an essential change in life style, the responsibilities incurred normally go beyond the possible limits of scientific prediction.

Occasional recharge in remote desert areas

It should be noted that even occasional rain storms may result in recharge in areas far from recognized intake areas, because vegetation does not compete for water. If the rain waters are quickly enough absorbed before evaporation can take place, by an aeolian sand cover for example which directly overlies permeable deposits, the potential recharge is maximized. Recent studies by Dincer, Al-Mugrin (Riyadh) and Zimmerman (1947) examined this phenomenon quantitatively in aeolian sand deposits covering permeable limestone aquifers in Eastern Saudi Arabia, receiving 80 mm rainfall/annum. They concluded that in ten years time about 30 mm rainfall would be recharged.

PROGRESS IN THE ORGANIZATION OF WATER RESOURCES MANAGEMENT

Inventory, administration and control of the national water resource

On a national level a tremendous effort has been made to quantify, administer and control the existing water resources. However, in spite of all the work already carried out, we are still far from the integrated management of the total water resource in the arid zone, which should be the final goal. All countries have made considerable progress in what one could call the first round of investigation. This first round is associated with studies of single items resulting in specific data collection, thematic maps covering certain regions or the country as a whole, of precipitation, watersheds, boreholes, aquifers and their different chemical and physical characteristics. Almost all countries have started the second round to compile all data in hydrological and hydrogeological maps and to initiate a centralized water resources filling system, which should be planned in such a way that it could be linked with a computer centre for more efficient data storage and data treatment.

However, very few countries are now ready for the third round, which is to exploit fully the central filing system and associated infrastructure. The exploitation of data is needed to improve and optimize the integrated use of the limited national water resource with the help of all massive investments made in the form of storage reservoirs, irrigation schemes, boreholes, pumping stations, water distribution systems, desalination plants, etc., which we could call the 'hardware', in an analogy with the computer sciences. In this connection, we could define the 'software' as being the complex of infrastructure enabling the effective management of the resource, and workable 'software' systems must follow the installation of hardware. The problem is to find the best balance between hardware and software, since too much emphasis on one aspect, normally the hardware as it is the more spectacular one, reduces the efficiency of the total system.

It should be well understood that in one country activities belonging to the three stages already mentioned can be executed at the same time, while in other cases one region can be far ahead of the other regions inside the same country. In those countries which are most advanced with respect to the overall management of their water resource, the responsibility for this management is given to one central organization such as the 'Division des Ressources en Eau' of Tunisia within the framework of the Direction des Ressources en Eau et en Sol, forming part of the Ministry of Agriculture. In Morocco we find a similar Division des Resources en Eau under the Direction de l'Hydraulique, being part of the Ministry of Public Works and Communications.

Algeria has regained the lost time resulting from its recent disrupted political history, with great success by the establishment of a Secretariat d'Etat à l'Hydraulique, directly responsible to the Head of State. Within this framework 'la Direction des Etudes du Milieu et de la Recherche Hydraulique' is carrying out the 'software' part of the task. This same method has been adopted in Jordan, known as the 'Natural Resources Authority' with its Hydrological Division, and in Libya under the name of General Water Authority. These centralized bodies have enabled very good progress to be made in a short space of time. In Saudi Arabia the Ministry of Agriculture and Water has been established to overcome the institutional difficulty often encountered through the separation of a study of groundwater from its application in a Ministry of Agriculture or a Ministry of Irrigation. In this way in the case of Saudi Arabia, the close connection between the investigation development and use of groundwater is guaranteed.

Well-established Ministries of Irrigation with a long tradition often exist in countries depending for their agriculture on irrigation with easily accessible river water. Because of their overall responsibility for the river water management and related irrigation, they were not able to administer groundwater development at the same time, certainly not outside the well-exploited river valley. This historical development is the reason why the total responsibility of the national surface plus groundwater resource is shared by different ministries. This has its repercussions on the data storage systems and consequently on the efficient exploitation of the total existing data.

Even though the river water and the groundwater may not be physically closely related, they may become interrelated by the policy chosen for their exploitation. Examples which will illustrate this are the recharge of excess flood waters in aquifers outside the river basins or the introduction of irrigation on the basis of river water outside a river basin. These measures are the normal consequences of an integrated utilization of limited water resources.

In many oil-producing countries, desalinated water is administered through the Ministry of Electricity and Water, because of the dual installation for these purposes. However, should desalinated waters be considered for recharge to maintain the groundwater reserves or to prevent or delay salt-water intrusion, a single authority to control all water-related matters may become a necessity.

Economic interest of regional approach

The actual knowledge of the national water resource varies from one region to the other and from one country to the other, inside the Arab world. However, it is often possible to estimate fairly accurately the probability of exceptional flood discharges, aquifer response, water application for crops on certain soils, etc., on the basis of comparison between catchments and aquifers with similar characteristics.

Much investment and research effort can be reduced by utilizing well-calibrated figures for specific associations of conditions, as for instance effective

rainfall figures with respect to vegetation and soil charactersitics. This implies that the Arab countries can help each other more effectively than any outside country can help them, on the basis of such a comparative approach, which has been proved a very positive methodology in hydrology. The principle of this approach gave rise to the establishment of a world-wide network of representative and experimental basins, which proved to be one of the great successes of the International Hydrological Decade (IHD).

Also in the field of continuing surveys and development of international river and groundwater basins, the Arab countries can unite their efforts. They have already done this to a certain extent, the Nile Basin Committee being the example with the longest tradition. Another example of regional collaboration is the Comité Maghrebin des Resources en Eau, CMRE or Maghreb Water Resources Committee, established in December 1973 during a regional meeting held in Algiers under the sponsorship of Unesco.

'Considering the similarity of climatic and meteorological characteristics as well as of the hydrological regimes and conditions of groundwater flow, given the analogy of problems to solve and difficulties to overcome, viewing the interest to join efforts, to exchange information, Algeria, Morocco and Tunisia' decided to co-ordinate their activities in the field of hydrology and hydrogeology (CMRE, 1973).

The co-ordination was specified to cover the exchange of data on research subjects of mutual interest, such as erosion control, artificial recharge, flood forecasting, a hydrogeological map of the Maghreb, and the training of specialists in these areas.

Under the sponsorship of the Arab Centre for Studies of Arid Zones and Dry Lands, established in Damascus in 1971, the joint exploration of the Hammad Basin, shared by Iraq, Jordan, Saudi Arabia and Syria, started on 3 November 1974. In collaboration with Egypt, Libya and the Sudan, UNESO has discussed a 'Study of the Nubian Sandstone Aquifers'. A number of meetings of regional specialists have taken place.

The UNESCO/UNDP study of the water resources of the western Sahara has been executed with great success in collaboration with Algeria and Tunisia and in the UNESCO/UNDP study of the 'Water Resources of the (non-Arab) Lake Chad Basin and Their Practical Use (FAO/UNDP project) to which contributed the four lake-sharing countries Nigeria, Cameroun, Niger and Chad, the policy of joint investigation of so-called transnational aquifers or river basins has been considered a sound and rational approach for regional development.

The UNESCO/UNDP Study of the 'Water Balance of the Western Limestone Complex of the Middle East', in collaboration with Jordan, Lebanon and Syria, has been approved by all countries involved. However, the recent disturbances in Lebanon have delayed the programme.

One of the efforts included in the United Nations General Assembly Resolutin 3337 on International Co-operation to combat desertification, is to assess the feasibility of transnational co-operative activity in assisting and where possible, reversing the desertification processes. The United Nations Environmental

Programme (UNEP) has been given primary responsibility for implementing the provisions of the resolutions. The idea is to work towards transnational intergovernmental agreements on subjects such as:

The establishment of a so-called green belt viewed as a mosaic involving range mangement, afforestation and improved land-use practices along the northern and southern boundary of the Sahara.

The management of livestock and rangelands to combat desertification into the Sudano-Sahelian regions.

The monitoring of desert processes and survey of natural resources in arid and semi-arid lands.

The management of the major regional aquifers.

The objectives of the last item is to arrive at a rational, economic and lasting exploration of the major regional aquifers of north-eastern Africa, and the Arabian Peninsula to combat desertification in these predominantly arid areas.

The short term objectives are:

To co-ordinate the ongoing and future operations undertaken by the countries for the exploration assessment and development of groundwater resources especially when such operations have intercountry implications.

To initiate additional pilot studies of a transnational nature to introduce appropriate methods and technologies to that effect.

To organize on an institutional basis a permanent intercountry co-operation for the management of the major regional aquifers.

To carry out an in-service training programme of national personnel at all levels.

To prepare documents such as maps and reports providing substantial basis and guidelines for the management of the major regional aquifers.

The projects will include the exploration of the Nubian Sandstone aquifers covering the southern part of Egypt, south-eastern Libya, north-eastern Chad and the north-west of Sudan. For this study, necessary consultation will be made with projects operating in Kufrah (Libya) and the New Valley (Egypt). Another project will explore and develop an untapped sandstone aquifer on the borders of Saudi Arabia, the Peoples' Democratic Republic of Yemen and the Yemen Arab Republic. The management of the limestone aquifers on the eastern border of the Arabian Peninsula, where economic growth through large-scale oil production has also increased water consumption to the extent that the existing water reserves may be exhausted within 30 years if immediate measures are not taken. These measures include the management of a large-scale desalination system using the cheap energy provided by otherwise unused flare gas.

THE CONSEQUENCES OF HUMAN INTERFERENCE IN THE HYDROLOGICAL CYCLE

The pressing needs of a rapidly increasing population for adequate water supplies has introduced two fundamental new concepts:

(a) The influence of man in the hydrological cycle.
(b) A fair understanding of the quantitative behaviour of water in the hydrological cycle.

The quantitative behaviour of water has become measurable thanks to the greater extent of man's interference in the hydrological cycle. For this reason the hydrological science, previously more qualitative and descriptive, has experienced an explosive development since World War II and in particular during the International Hydrological Decade from 1965 to 1975, launched by UNESCO.

The most striking quality of this development was its quantitative character. The availability of systematic recordings, collected from all parts of the world and covering time intervals of different lengths, also made this science amenable to a mathematical approach. Physical, electrical and mathematical models of different types, have simulated the dynamic parameters of hydrological systems and induced changes at a known rate, have been simulated in succession in the reduced time scale of the respective models. The aim was to match the resulting parameters with the corresponding parameters of reality.

By building up a good understanding of the basic interrelationship between the parameters, extrapolation for the future can be tried out in the models. Feeding the models with a series of estimated data based on probability in the respective model time scale, actual trends of development can be inferred. In this way modelling becomes a sophisticated method for quantitative prediction, and can also be useful for studying and comparing alternative solutions of one problem. Although globally matching models may already be of great use for training purposes, accurate matching with reality is required for reliable prediction. A model can only be made to match reality if the latter is well known by judicious choice of field observation. It should be well understood that models can only predict these parameters for which they are designed.

The increasing dimensions of man's interference in the hydrological cycle, either by engineering constructions, groundwater withdrawals, or any other method for re-routing the original massive surface – and/or groundwater-flow – enlarge also the side-effects which can increase at exponential rates. For instance doubling the length of the edge of a cube, increases the volume by the third power of two, to eight times (Aboukhaled *et al.*, 1975). Hitherto neglected unknown side-effects may appear today as new significant parameters. In many cases hidden side-effects appeared outside the scientific scope of conventional

control observations of the induced change. This made a multi-disciplinary approach, and accordingly interdisciplinary team work, an absolute necessity to cope with the problems evoked. With even greater interference in the self-regulatory and self-regenerating mechanism of the hydrological cycle, new side-effects become perceptible either with new parameters, or parameters already known from other fields of science.

Interference on an unprecedented scale can only be tested in models as far as the conventional parameters are concerned. Therefore, only the real experiment carried out on a real-world scale will show the complete set of consequences from which we might adjust our scientific understanding, on condition that we are alert enough to perceive them. Newly acquired and sometimes bitter experience has to be incorporated in the latest paradigm of modern science to be used in future studies and management.

Part II

The Contribution of Science and Technology

SURFACE WATER

The Aswan High Dam as the only answer to pressing needs

Among the large rivers of the world, the Nile represents a unique case, as it is the only river which traverses such a large tract of extreme aridity and which still has been able to build up a prototype delta, this being the only one on the southern Mediterranean coast.

This is possible through the Nile's twofold supply:

(a) The steady inexhaustible supply from Lake Victoria drainage area, south of the Equator, fed by rains independent of the monsoonal air circulation. This source always guarantees the minimum flow of the river.
(b) The wild torrential rivers draining the Ethiopian Highlands swept by the monsoonal rains in the summer of the northern hemisphere (examples are the Sobat, Blue Nile and Atbara). These waters provide the yearly flood charged with the life-bringing silt which produced the fertile lands of Egypt.

The Nile basin covering one-tenth of the African continent is shared by nine countries. From latitudes 14° N to 31° N it traverses the arid zone of the Sudan and the whole of Egypt. Its waters represent the only renewable source of water in this zone and as such it compensates for the absence of rainfall.

Egypt's agricultural production depends in the first place on how well the Nile's water can be distributed in space and time to meet the present and potential future requirements. As a result regulations of the river water started as early as 1847 when the Delta Barrage provided an ingenious system of dams and regulators distributing the Nile waters over the entire Delta.

The Nile waters supply, although fluctuating enormously in discharge, has always been considered sufficient for all foreseeable demands, until today when, through the Egyptian population explosion of the last three decades, it has to support a population of 39 millions. This population lives in the valley of Upper Egypt, which is about 9 km wide, and the Delta of Lower Egypt, with a total irrigated area of 6.5 million feddans or 27 300 km^2. That means that each square kilometre, producing sometimes as much as three or four crops per year (average figure for the total cultivable area is 1.65 crops per year), has to feed 1390 persons (Kinawy, 1975).

By the 1950s river regulation was no longer sufficient. Even the construction of several dams, either to hold back part of the flood waters to be released at a later moment in the year when supplies were running short, or to lift the water surface to allow inflow in irrigation canals at higher levels, could not solve the problems. Over-year storage or, in other words, complete control of the river

became an immediate necessity in Egypt. So the Saad El Ali or Aswan High Dam was erected for the following main purposes:

(a) To protect Egypt against the inundations caused by the Nile floods and, on the other hand, to guarantee the water requirements for the areas under cultivation even in years of low supply.
(b) To generate electric power for industrialization.
(c) To expand the cultivated area beyond the traditional limits of the Nile Valley.
(d) To improve navigation conditions.
(e) To employ thousands of labourers in the reclamation of new lands and industries.

Ecological consequences of the Aswan High Dam

The closure of the Nile at Aswan has introduced radical changes in the ecology of the storage reservoir area, Lake Nasser and Lake Nubia and the Nile Valley.

1. All waters of the Nile are utilized by man and in principle only drainage waters reach the Mediterranean.
2. The silt is dropped at the entrance of the storage reservoir, where a new delta is formed, mainly between 420 and 300 km upstream of the Aswan High Dam. This is mainly upstream of the second cataract in Sudan, in the part of the storage reservoir which is called Lake Nubia (Entz, 1973).
3. As a consequence of 2, silt-free water released from the dam is now eroding the river bed (so-called degradation) in its effort to establish a new equilibrium condition. The only way to minimize this effect is to diminish the gradient (Lutfy *et al.,* 1969). Six additional barrier dams between Aswan and the Delta Barrage, in addition to the three existing ones (see Table 2), are proposed to solve this problem (National Research Centre, 1976).
4. About 50 million tons of Nile silt, which was spread yearly over the land by the river floods*, must now be replaced by fertilizers. Fertilizers are now partly produced with electricity generated by the High Dam, and others have to be imported.†

*In the Roseires reservoir and Khashm el Girba reservoir, silt is also deposited (see Nile diagram).

† Present economically justified consumption is estimated to be:

c. 3×10^6 ton nitrogen fertilizer (on basis of 15.5 N).
c. 5.5×10^5 ton phosphate fertilizer (single superphosphate).
c. 5×10^3 ton potassium fertilizer (K phosphate).
From this amount Egypt produced in 1976.
c. 1.3×10^6 ton N.
c. 3×10^4 ton P.

By 1980 Egypt will cover its own fertilizer needs and will become an exporting country (Siegel, 1976).

5. As a consequence of the disturbance of the dynamic equilibrium between the supply to, and the losses of sediment from the shores, erosion of the Delta coast takes place. The UNDP/UNESCO Coastal Erosion Project studies and analyses this phenomenon in collaboration with the Academy of Scientific Research and Technology, in order to introduce corrective measures.
6. The absence of periodic water level fluctuations (previously at Aswan about 7.5 m, at Cairo 4.5 m and 2 m in the Delta), reducing riverflow to relatively constant and low levels, has activated certain time-dependent soil-mechanical processes progressively modifying the soil structure until a new equilibrium is reached.
7. The previous factor, associated with the eutrophication process caused by the amount of fertilizers drained into the river, has created a profound change in aquatic organic life conditions in the river.
8. Especially in the region around Cairo, where almost one-third of the country's total population is concentrated along with industrial centres, the river has become sensitive to pollution as the Nile no longer flushes clean during the flood.*
9. Land reclamation projects (Nubariyah and Komombo) have caused water-logging and salinity, because of a considerable rise in the water table of up to 4 m/annum. This was due to over-irrigation and economizing on drainage works, as the original groundwater table was 20–60 m below the surface level. In the meantime, the groundwater response on the induced change has not been sufficiently monitored. Irrigation waters pumped stepwise from the Nile Valley up to the bordering desert plateau infiltrated into the desert crust. This water, dissolving the salty components of the subsoil became saline groundwater and drained back into the irrigation canals polluting the irrigation waters and consequently affecting the crops (Saad *et al.*, 1972; Schulze *et al.*, 1973).†
10. The fishes depending for their nutrition on the Nile silt discharged into the Mediterranean have disappeared, while, on the other hand, the inland fish

*It is thanks to its initial outstanding chemical quality, that the Nile can absorb a great deal of chemical pollution before critical levels are reached. The dissolved solids content is about 200–300 mg/l in the upper parts of the Nile Delta. In this respect the Nile is representative of all rivers draining the African Shield zone, surrounded by continental clastical detritus deposits, all leached out by tropical rains. The Euphrates drains the precipitates (limestone, dolomites, etc.) and evaporates (gypsum, rock-salt, etc.) of the old Tethys geosynclinal belt to be found in the Mediterranean zone and its eastern extension. This river has an initial salinity reaching 600 mg/l (Al Badry *et al.*, 1972; Ramadan, 1972). In electrical conductivity units of μmho: the Euphrates upstream of Baghdad varies from 400 to 850 μmho; the Nile until the upper part of the Delta varies from 200 to 400 μmho.

† UNESCO gave directives to analyse the phenomenon quantitatively and to determine corrective treatment (Gischler, 1973a). This is now being executed in part by the UNDP/FAO project: 'Control of water-logging and salinity in the newly reclaimed areas'. An additional UNESCO-executed Funds-in-Trust project: 'Study of the groundwater basin in the western Nile Delta and adjacent areas of the north-western desert in Egypt', was prepared but took shape in its original form.

Table 2. Some characteristics of dams, reservoirs and swamps in the Nile Basin (numbers refer to corresponding numbers in the Nile diagram)

No.	Name	Year of completion	Possible rise of water level (m)	Volume (km^3)	Surface and/or length reservoir	Losses (evaporation) ($10^6 m^3$)
1	Edfina Sudd	(bank for protection against marine intrusion)				
2	Faraskur Sudd					
3	Zita barrage	1902	3.80			
4	Delta barrage	1847	1.50			
		1890	3.50			
	Mohamed Ali barrage	1939	4.20			
5	Assiut barrage	1902	3.50			
		1933	3.50			
6	Nag Hammadi barrage	1909	4.65			
7	Esna barrage	1909	2.00			
8	Aswan Dam	1902	18.00	1.0	225 km	
		1912	25.00	2.4		
		1934	34.00	6.3	360 km	
9	Aswan High Dam	1970	97.00	164.0	500 km 6000 km^2	10 000
10	Khashm el Girba dam	1964	(20)			60
11	Sennar dam	1925	16		140 km	280
12	Roseires dam	1966	50	0.45	290 km	450
13	Frontier Sudan–Ethiopia					
14	Lake Tana				3100 km^2	Equal rainfall
15	Jabal Aulia dam	1937	6.55	3.6	500 km	2 800
16	Baro Pibor Sobat Swamp					4 000
17	Bahr el Ghazal Swamp					15 000
18	Bahr el Jabal Swamp				8300 km^2	12 000
19	Frontier Sudan–Uganda					
20	Lake Albert				5300 km^2	Less rainfall
21	Lake Edward				2200 km^2	Slightly less rainfall
22	Lake Kioga					
23	Owen Falls					
24	Lake Victoria				67000 km^2	Slightly less rainfall

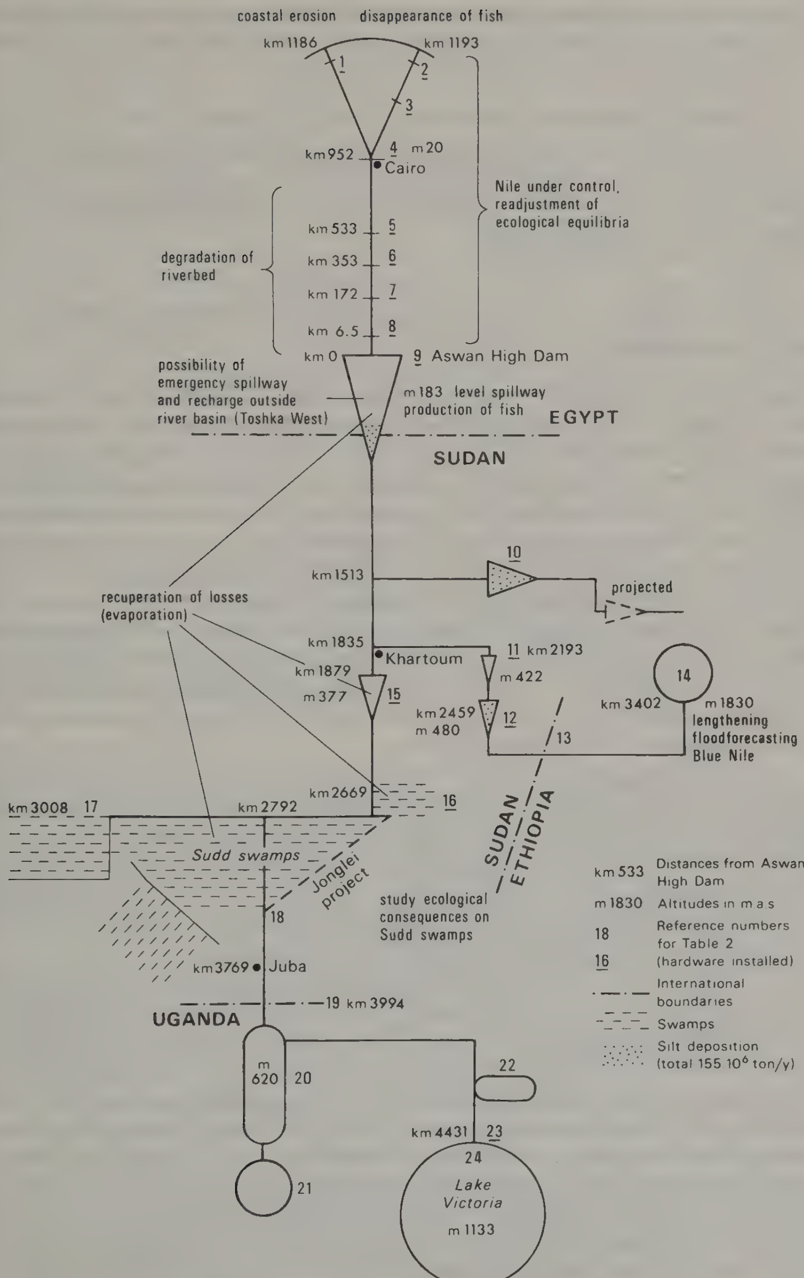

Fig. 3. Diagram of the Nile showing the river works.

production in Lake Nasser and Lake Nubia largely compensates for this effect, due to the high primary production of the High Dam reservoir waters.

The rapidly increased fish production gradually exceeding 20 000 ton/annum, in Lake Nasser/Lake Nubia, was the result of lake conditions, gradually introduced since 1902 (see Table 2). (Dekker, 1972; Hurst, 1946, 1957; Hydrobiological Research Unit, 1963–73; Kinawy, 1975; National Research Centre, 1976; Nicola, 1971a, b; Rzoska, 1976).

Introduction of a new environment in man-made lakes (Lake Nasser/Nubia, Lake Tharthar (Iraq))

The large water masses of the man-made lakes stop the horizontal river flow and force deposition of the sediment load. Increasing transparency of the water favours light penetration and activates the growth of phytoplankton (primary production) and consequently the production of oxygen by photosynthesis. This in its turn stimulates secondary production. In deep lakes exceeding about 30 m a new circulation pattern sets in, activated by a physical mechanism based on the exchange of heat between the lake's surface and the atmosphere.

In winter the cooled surface waters sink, to be replaced by lighter, warmer waters from deeper zones. In this way a complete turn-over can take place if the minimum surface temperature (above 4°C) is lower than the temperature of the water at the bottom (if not, a dead zone will develop at the bottom). This turn-over process results in an even distribution of the oxygen produced at the surface throughout the total lake volume.

In the summer half-year the surface layers heat up and stagnate the winter circulation. From April to July excessive heating of Lake Nasser and Lake Nubia gradually creates a stratification, which even the wind's action cannot destroy. At 10–20 m depth, depending on the light penetration, a more or less pronounced interface, called a thermocline, separates the warmer surface layers from the cooler water of the deeper zone, whence the oxygen is gradually depleted restricting aerobic life conditions to the upper zone.

In the summer the surface layers of Lake Nasser reach temperatures of over 30°C. The gradual cooling-off of the surface in the winter period then destroys the stratification again and reactivates the winter circulation, re-establishing aerobic life conditions throughout the entire lake volume. The turbulent flood waters coming from the south, from July to September, also have this effect, decreasing for this reason the depth of the previously mentioned interface (thermocline) towards the south (Entz, 1970; Rzoska, 1976; Gischler, 1974a).

This phenomenon has been observed with slight modifications in the Roseires reservoirs, in Lake Nasser/Nubia, and in the Tharthar lake, created since 1957 when the Tigris flood waters were diverted into the Wadi Tharthar Depression north of Baghdad. When the downstream canal, connecting the Tharthar lake to the Eupharates, is completed (1977), a thorough understanding of Lake Tharthar

ecology will be of great help in finding the best way (in timing and quantitative admixture) to mix lake waters with the Euphrates waters in order to optimize conditions downstream (Al Badry *et al.*, 1972; Gischler, 1973a; Hydrobiological Research Unit, 1963–73; Nedeco, 1959).

Conclusions drawn from the closure of the Nile

The last two paragraphs summarize some consequences of the closure of the Nile by the Aswan High Dam. However, they prove sufficiently that when a river is completely controlled, it also loses those self-regulating and self-regenerating capacities which stabilize certain characteristics of the river in question, under at least partly free-flowing conditions.

This is clearly observed, for instance, in the upstream Roseires reservoir, where, during the Blue Nile flooding period, which causes the water to rise an average 9.5 m, river conditions are regenerated in the reservoir. The stratification is destroyed, and previously deposited silt is partly taken up again and vented from the reservoir.

Since complete river control has created an essentially new situation, corrective treatment of the side-effects cannot be based only on old and very long scientific records of the river.* The corrective treatment has to come from modern science and technology, analysing the new set of processes triggered by the closure of the High Dam, and helping to reach stabilization in a new overall equilibrium by action in the field. This should be guided by proper and new information – concerning the river, the soil, the population, land cultivation and treatments – and adequate training.

Flood forecasting

A beginning of the impoundment of the Aswan High Dam Storage Reservoir (Lake Nasser and Lake Nubia) was made in 1964, while the dam itself was completed in 1970. So far water has been released from the reservoir to satisfy simultaneously the power and water requirements downstream. The difference between the annual inflows and the water released was used to fill up the reservoir: first the dead storage 30 km^3 reserved for silt up to 145 m above sea-level, then the live storage 90 km^3 up to a level of 175 m. This level was reached on 12 October 1975, much earlier than expected.

The effective management of the reservoir water in the future has to take into account the yearly inflow from upstream. The remaining space up to the

*That the Nile control has created a unique precedent from which the outside world is eager to learn, is demonstrated by the joint initiative of the University of Michigan (USA) and the Egyptian National Research Centre to make a water quality study of Lake Nasser and the Nile. This project is being executed within the framework of the Egyptian Academy of Scientific Research and Technology and is financially supported by the Environmental Protection Agency of the USA and the Ford Foundation. Since the beginning of 1975 all so far known biochemical characteristics have been monitored in great detail. This will continue for a period of five years, while UNESCO/ROSTAS is participating on a consulting basis. (National Research Centre, 1976).

spill-way level which according to the official figures at 183 m, contains 45 km^3 but possibly more, is to be allowed for floods during high discharge years, as well as for annual regulation.

So far the forecasting period for floods coming from the Blue Nile, contributing 60 per cent of the total annual Nile flow, depends on the first observations communicated from the Ethiopian–Sudanese border. The time taken for fluctuations in the flood season originating at this point to reach Aswan, 2572 km along the river, is approximately 14 days. This forecasting time could be lengthened considerably by studying rainfall runoff interrelationships in Ethiopia, and also by exploiting the data collected by the weather satellites.

Just as driving a car in poor visibility gives the driver little time to react to unexpected events, so a dam operator dependent on a forecasting system covering a short period has little time to regulate the outflow within the stipulated constraints of:

(a) The maximum water requirements downstream.
(b) The maximum tolerated discharge and flow velocity in the downstream river channel if excessive degradation or other damage is to be avoided and if large-scale disasters are to be prevented.

In this connection 'The Assistance to the Hydraulic Research and Experiment Station, Delta Barrage' supplied by the United Nations is worth mentioning. This project envisages among other things the definition, specification and installation of a suitable telemetering system in the Nile river downstream from Aswan.

The distribution of river discharges or rainfall follows approximately the Gaussian normal curve. However, it should be noted that most of these distributions are only Gaussian when no account is taken of the order in which they occur. It usually happens that high and low years tend to occur in clusters, a fact which is well known in the case of climatic events, and also in the case of the Nile, being the longest recorded in the world.

The same circulation system which caused the Sahelian droughts has influenced to a large extent the Nile discharges, since 1964. The Aswan High Dam prevented Egypt from 'drying out' during the year 1972–73 when flood discharge was exceptionally low. A number of international and national agencies, including UNESCO, are attempting to extend the forecasting period to allow more effective management of the Nile waters, especially those of the Blue Nile.

That water levels can rise very quickly was proved by the large Nile flood of 1975. From 12 September to 12 October, the lake level rose about 3 m, which corresponds with an increase in volume of 16–19 km^3. Since the hardware has been installed to enable the over-year storage of the Nile at Aswan, the software should be provided in time to work out the most efficient operation of this new management potential (see Table 2).

It is worthwhile noting that in the continuation of the Kher Tushka West there exists a natural depression in the water-divide between the Nile Basin and the New Valley, south of Kharga. The altitude of the depression is about equal to the level of the artificial spillway of the Aswan High Dam. A study has been

recommended on the possibility of arranging this depression as an emergency spillway in case of Nile floods of unforeseen dimensions. In a second phase recharge possibilities might be studied at the other side of the divide (Gischler, 1974b; Kamal *et al.*, 1974b). This subject has received the full attention of the authorities, and alternative solutions are being considered.

Erosion

Flood forecasting studies linked with soil conservation in the upstream part of a river (corresponding with the headwater region in semi-arid regions) are an economically constructive combination of efforts. For the floods generated by torrential rains, which remove the soil in the upstream part, are also the transporting agent for the eroded material. This sediment load then is dumped in the storage reservoirs in so far as it cannot be vented from the reservoirs.

Suitable dam sites exist in the border zone of the mountainous massifs, just upstream of the wide plains which need irrigation waters in order to become productive, and engineering works at these sites could modify significantly the peak flow characteristics of the Blue Nile. In this connection soil conservation studies related to the research on flood generation in Ethiopia and of the peak flow along the Blue Nile could very well result in the initiation of corrective treatment of the silting-up of Roseires and Khashm el Girba reservoirs.

In 1966 the Roseires storage reservoir reached a maximum depth of 50 m, while in February 1975 the maximum depth measured was only 17 m.* The Khashm el Girba reservoir on the Atbara should silt up even more quickly. Since a new dam is already projected upstream of the latter reservoir in the Taccaze river, a tributary of the Atbara, the solution of this problem is very important.

In the Maghreb countries, with natural conditions comparable to the Ethiopian Highlands, soil erosion is a priority problem. This evil is fostered by the following combination of factors:

(a) Heavy well-separated rain showers, which soon result in rain intensities exceeding the infiltration capacity of the soil.
(b) Low permeability of easily removable soils like weathered schists or basalts, marls and unconsolidated sediments like loess, which create a high runoff coefficient, rich in suspended matter.
(c) Slopes with the right inclination and of sufficient length, without much vegetation, contributing to an intensive furrowing of the slopes and consequent removal of the good soil.

In soil conservation programmes, in principle, the product of the mass of the runoff emulsion and the square power of its velocity $1/2\,m\,V^2$, being the kinetic

*The three turbines at Roseires normally produce 60 megawatts during the flood period. This year they produced only six because an island was formed just above the Power House. They also encountered many difficulties with the cooling system on account of the high silt content transported this year' (extract from a letter from the Hydrobiological Research Unit, University of Khartoum, dated 14 October 1975).

energy, should not be allowed to build up and reach high values. This can be achieved by fixing the soils by vegetation, which at the same time intercepts rainfall and forms obstacles for the surface runoff, preventing it from gaining speed. Small obstacles produced in the flood-generating zones by land treatment parallel to the altitude lines (as for instance ploughing) reduces $1/2\,m\,V^2$ each time to zero in the zone where water has not yet formed one coherent mass. At the same time the possibility of infiltration is increased and under these circumstances the application of fertilizers, which otherwise could be washed away, can also be reduced drastically.

Once the kinetic energy has reached high values, vegetation screens of 20 m wide parallel to contours are required. Such barriers take considerable time to grow. Alternatively expensive structural installations are needed to slow the erosive power of surface runoff.

When the sediment load finally reaches the storage reservoir, it reduces the storage capacity and shortens the life of the reservoir. The volume of sediment transported in suspension can be accurately computed by periodical measurement in the storage reservoir. This volume should be corrected for the vented sediment, if any.

In semi-arid regions, erosion rates of 1000–2000 ton/km^2/annum are normal, while under moderate climatic conditions, 100–600 ton/km^2/annum are common. In Algeria, where erosion is particularly severe, erosion rates reach over 2000 ton/km^2/annum and may even reach up to 10 000 ton/km^2/annum in very degraded areas of the Aures massif near Constantine (DEMRH, 1973d; Gignoux, 1955). As a result small storage reservoirs are not considered to be economically feasible. In Algeria there are already several examples of hydraulic or mechanical removal of sediment from reservoirs. Although this is a costly enterprise at 1 Algerian dinar/m^3 it is often the only means of restoring the storage capacity.*

The ideal is when the sediment is accumulated in the deepest storage part of the reservoirs designated as a sediment pool. In Lake Nasser the Nile silt will never reach this zone as it is mainly deposited upstream at the higher elevations of Lake Nubia.

In the semi-arid limestone massifs of the Middle East, karst phenomenon prevent the surface runoff coefficient reaching extremely high values. Also, the rivers are largely fed by silt-free spring waters. As a consequence, erosion is not of the first importance in such areas.

Evaporation

Under arid and semi-arid conditions evaporation always exceeds rainfall, if calculated over the length of one year. For this reason evaporation presents an

*The Comité Maghrebin des Ressources en Eau requested UNESCO to organize a world symposium on erosion and sediment transport. As a result a symposium was organized in June 1977. Tunisia has also shown concern about soil erosion and has asked for UNESCO's assistance in an erosion control project in the region of Kairoun, Sbeitla and in the very degraded Oued Zeroud drainage basin in the middle of the country.

even more serious drawback to the surface storage of water than the problem of sediment deposition (see erosion in the preceding section). Only the absence, at present, of alternative storage possibilities has forced engineers to apply the principle of surface storage behind dams under arid and semi-arid conditions.

In Morocco, for instance, the total storage potential in 1974 was 6.1 km^3 divided between 23 storage reservoirs. This potential was increased in 1977 to 7.2 km^3. In the Euphrates valley, four dams are under construction in Turkey, of which the Keban dam, after some delay, is completed and is filling up with water. In Syria impoundment has been under way for some years behind the large Tabga dam. This has created a water shortage in Iraq, where a dam near Haditha will be constructed to lift the lowered river level. In this way water can again be introduced to the irrigation canals branching off stream from the new dam.

Although these dams will have a regulating effect on the river, evaporation will take its share, not only from the storage lakes but also from the irrigated plots, in total about 2 800 000 ha spread over the three countries of Turkey, Syria and Iraq. It will be the task of the drainage engineers and the general management of the Euphrates river waters to avoid accumulation of dissolved solids at the soil surface where soil moisture evaporates (Gischler, 1973c).

In Table 2 (page 24) it can be seen that the toll paid to evaporation by the Nile is extremely high (although absorption losses into the banks have also been included in these figures):

(a) In the Bahr el Jabal swamps, the losses are equivalent to the height of $12\,km^3/8300\,km^2 = 1.4$ m/annum (Hurst *et al.*, 1938, 1946). This has been calculated on the basis of the average difference in river discharge, upstream and downstream of these swamps. Of course the average rainfall of 0.9 m/annum is excluded. This makes the evapotranspiration of the swamp vegetation 1.4 + 0.9 m, that is 2.3 m/annum.

(b) The Baro, Pibor, Sobat swamps and the Bahr el Ghazal swamps are less defined in area as they vary more in surface with the seasons. However, overall losses are estimated to be respectively 4 and 15 km^3/annum.

(c) The losses in the Jabal Aulia reservoir are $2.8\,km^3/600\,km^2 = 4.7$ m/annum. This figure may be so high because of the absorption of water into the wide bank zones, the shallow depth of the reservoirs, and the abundance of water hyacinths from June to November block the navigation lock completely. This latter phenomenon is due to the absence of the steady northern winds in that period, and to the mode of exploitation of the storage reservoir. The water consumption of the water hyacinths can easily double that of the evaporation of the free water surface (Obeid, 1975).

(d) The losses in Lake Nasser/Lake Nubia according to the official figures are $10\,km^3/5000\,km^2 = 2.0$ m/annum. However, since the average surface of the lake has been underestimated, it is justified on the basis of the morphometrical tables prepared by Entz to adopt 6000 km^2 as the

average surface if the lake will fluctuate between 175 and 183 m (Entz, 1973; Nicola, 1971b). Using this figure the losses would be $10 km^3/6000 km^2 = 1.7$ m/annum. This figure is extremely low, as the evaporation from the free water surface according to the Penman formula, applied to the atmosphere conditions in Aswan, amounts already to 2.20 metres per year. (Aboukhaled *et al.*, 1975).

For comparison it is worthwhile to list the average open water evaporation rates from the surrounding region, as has been done in Table 3. The last figure of Table 3 has probably been calculated with the highest accuracy, as continuous measurements were taken over a period of many years.

Table 4 shows estimated values for open water evaporation through the year at Aswan at 24° latitude and at Dongola at 19° latitude, in millimetres per day. The maximum values are underlined in Table 4 (Adam, 1973; Aboukhaled, 1975). At 19° latitude a slight effect of the monsoon is still apparent, causing some cloud coverage in July and August. Therefore it is probable that the evaporation from open water may be at its maximum in the Lake Nubia area and

Table 3. Estimated yearly evaporation values from open water

Latitude	Locality	E. (m)	Remarks
34°	Lake Tharthar (Iraq)	2.25 (corrected value for shape of reservoir)	Waterna, NEDECO, 1958
25–30°	Arabian Gulf	2.2–2.5	
24°	Aswan (Egypt)	2.2 (Penman)	Aboukhaled *et al.*, FAO, 1975
21–24°	Lake Nasser/ Lake Nubia		
19°	Dongola	2.5 (Penman)	Adam, H. S., Sudan Meteorological Dept., 1973
14°	Lake Chad	2.29	Bouchardeau, A., Lefevre, R., OSTROM, 1967

Table 4. Mean monthly values for open water evaporation in mm/day for Aswan 24° lat. and Dongela 19° lat.

Northern latitude	J	F	M	A	M	J	J	A	S	O	N	D	Yearly total (mm)
24°	2.76	4.00	5.57	6.95	8.14	8.51	7.98	7.87	7.07	5.67	4.00	2.94	2190
19°	4.30	5.30	6.60	8.10	8.10	8.90	7.70	7.60	7.60	7.20	5.30	4.40	2460

gradually decrease towards the values as given for 24° latitude. This hypothesis is confirmed by the maximum of solar radiation in excess of 220 k calories/cm²/ annum which is found over the northern Sudan near Wadi Halfa, while Dongola is located in the zone between 210 and 220 k calories/cm²/annum* (Sid-Ahmed, 1975).

Further critical comparison between these values reveals that the average cloud cover above Lake Nasser/Lake Nubia is lower than above Lake Chad, and the average relative humidity is also lower. There is a similar relationship with the Arabian Gulf area. In Lake Tharthar, however, the minimum temperature of the waters approaches 0°C and this effects the total evaporation from the lake. In contrast the minimum temperature measured by the author in the deepest point of Lake Nasser in February 1974, after an exceptionally cold period in January 1974, was 15°C, at which time the surface was already heating up again (Burdon, 1972; Nedeco, 1959; Thomas, 1973). On the other hand the feather-shaped Lake Nasser/Lake Nubia is deep in its central part where the original Nile bed is located. Here depths of around 100 m occur. In spite of this the average depth is 25 m, while the average depth of the wide Khor Khalabsha, a wide inlet north west of the lake with a surface of 620 km² approaches only 10 m. All depths are calculated from an assumed water level of 180 m above sea-level (Entz, 1973).

Taking into account all the above evidence a total annual overall loss of 2.5 m mainly through evaporation in Lake Nasser/Lake Nubia seems to be justified. This figure would result in total losses of the Aswan High Dam storage reservoir of about 15 km³, for water levels fluctuating from 175 to 183 m above sea-level. This figure is probably conservative and evaporation rates are likely to be higher rather than lower.

Recuperation of losses

The Sudd swamps

At present the Jonglei Canal project in the south of Sudan has started to recover a total of 4.8 km³† of the 12 km³ of water lost in evapotranspiration in the Bahr el Jabal swamps (Abdel Megeed, 1974).

The flow in the Bahr el Jabal will be reduced by excavating the Jonglei Diversion Canal around the swamp area (see Nile diagram, Fig. 3). The canal will be about 300 km long with a capacity of 20 000 000 m³/day. This is the first implementation of the Nile Waters Agreement signed in 1959, reading:

> 'The Republic of the Sudan in agreement with the United Arab Republic shall construct projects for the increase of the river yield by preventing losses of waters of the Nile Basin in the swamps of the Bahr el Jabal, Bahr el Zaraf, Bahr el Ghazal and its tributaries, and the White Nile Basin. The net yield of

* The average received at the earth surface is 116 kcalories/cm²/annum.

†4.8 km³ should be diminished by actual downstream transmission losses as far as Aswan to calculate the Egyptian share.

these projects shall be divided equally between the two Republics and each of them shall contribute equally to the cost' (Abdel Megeed, 1974; Abdel Alier, 1974).

Of course the drainage of this huge swamp area would have important ecological consequences. Therefore the United Nations has given first priority to an integrated interagency project to study the possible side-effects in order to reduce harmful consequences to a minimum (Gischler, 1975a).

The area supports almost one million semi-nomads with their numerous cattle and a great wealth of unique swamp vegetation and wild life (Evans-Pritchard, 1940).

Storage reservoirs

The suppression of evaporation losses in large storage lakes as a whole, unlike in small tanks, is for the time being not technologically feasible, as great water depth and wind action create major problems. It is however possible that in ponds, small storage reservoirs, or certain parts of larger lakes, evaporation can be reduced. This can be done by liquid chemicals that automatically spread out, forming a sealing layer across the surface, or by blocks, rafts or beads that float on the water surface thus reducing the area in which evaporation can occur. In fact the solution of this problem depends on the evaporation rates versus the need for more water, plus the cost of the cheapest way to reduce the free water surface. So the suppression of evaporation is in principle an economic problem which may become more interesting when cheaper means become available (Ad Hoc Panel, 1974).

Under the conditions existing in the Lake Nasser–Lake Nubia area, each feddan (0.42 ha) protected against evaporation with a realistic 80 per cent efficiency rate, will provide about 8000 m^3/annum. Such a measure would be unrealistic for the central part of the lake, but for a sheltered inlet separated from the main lake by a narrow passage, this could be considered feasible. Porous (concrete) blocks made of local available materials, sprayed with plastic or a similar substance, to make them float, could be used as a covering material.

Also, certain shallow parts of the lake could be kept dry, by erecting a dike. Behind this dike, irrigation could be undertaken. In this way those parts with the highest evaporation rates could be excluded from the active lake surface, and the surplus water gained by this method could be re-routed in a more profitable way.

Conversion of a drawback into a driving force

Recognizing the major importance of evaporation in arid zones, it needs only imagination to convert its negative effects into the positive driving force which underlies the generation of power by diverting sea water into deep natural

depressions. The Qattara project is based on this principle, for which the bilateral agreement between West Germany and Egypt has been signed (Fig. 3).

Through a 75 km long channel, sea water will be diverted from a point near to Al Alamein on the Mediterranean to the Qattara Depression. Here this water will fall into the depression reaching 135 m below sea-level, and in passing through turbines electric power will be generated. A salt lake will be created like the Dead Sea, with a surface of about 6000 km^2. The constant inflow of water from the Mediterranean (600 m^3/sec), will be counterbalanced by the rate of evaporation from the expanding water surface until an equilibrium has been established. In fact every preconceived water level until sea level could be maintained by regulating the inflow as a function of the total evaporation from the water surface. Preference so far has to be given to some specific low lake level depending on the shape of the depression, to maximize the energy output of the system and to avoid, as much as possible, contamination of neighbouring freshwater aquifers. Of course there will be side-effects which should be studied in time, but all these side-effects will not necessarily be negative in character.

The idea of this scheme can be traced back to World War II, when Frederick Bassler, a young officer in Rommel's Africa Corps, made a first cursory inspection of the vast depression. Today Bassler is a university professor at Darmstadt and an expert in hydraulic engineering. But even Bassler's idea was not original, as at the end of the last century a French geologist called Lartet, one of the first explorers of Palestine, suggested perforating a tunnel from the Mediterranean to the Dead Sea to exploit for power generation the difference in altitude of 400 m, and high potential evaporation in the depression (Gignoux *et al.*, 1955). Although scientists and engineers have long been aware of the tremendous potentialities of evaporation in arid zones, it took many years and it needed examples like Lake Nasser–Lake Nubia before public opinion was prepared to take the risk of financing such projects.

GROUNDWATERS IN PRIMARY PERMEABLE MATERIAL

Geology of sandstones of Nubian facies

The sandstone of Nubian facies form the present aquifers underlying much of the Arabian Peninsula and the Sahara. Their name derives from the outcrops in Nubia in the north of the Sudan and the south of Egypt (Fig. 1). The Nubian facies has been protected by the rigid substratum of the basement complex which were fused and cratonized into one immobile mass in the Precambrian. They derive from the Precambrian and from reworked sandy Palaeozoic deposits and have not been altered by metamorphic processes. During the lengthy process of peneplanation they have gradually been deposited in the periphery of the culminating outcropping regions of the old basement complex, on the so-called stable shelf and even beyond this area on the unstable shelf where the Nubian facies reduce quickly and progressively in thickness.

Their often arkosic character, rapid changes in facies, crossbedding, lack of fossils, although fossil wood and plants are common, witness the essentially continental origin of the Nubian Sandstones. It is believed that the climate was predominantly hot and semi-arid. Over these deserts of moderate relief weathered products of granite and related plutonic rocks were moved, shifted and rounded by aeolian forces. However at intervals there were heavy, possibly local rains, leading to sheet flow and braided river systems which swept the eroded products into depressions occupied by shallow lakes, coastal lagoons, or sebkhas in which also, fine-grained sediments such as clays and sandstone could be deposited over large distances. Often the sandstones are well lithified, the cement being formed of iron, manganese or other oxides which coat quartz. Silicification into quartzite is unusual and carbonate cement does not occur. Stratigraphic correlation is only possible where the sandstones with Nubian facies are interrelated with dateable marine deposits, on account of their characteristic fossil content. In this connection Saudi Arabia offers the best locality for stratigraphic studies. Here their reoccurrence on the eastward-tilted Arabian shield from Cambrian to the Middle Upper Cretaceous must be seen as a main characteristic (Burdon, 1976).

However, recent oil exploration revealed that from Dakhla to the south a fairly complete succession of Nubian type sandstone is exposed with a thickness of about 4000 m from the Precambrian substratum in the south to the Maastrichtian marine Dakhla shales in the north. Two marine shales of remarkable continuity of slightly less than 100 m thickness were traced, located at respectively 30 and 75 per cent from the base in the overall profile. The lack of feldspar remains tend to exclude in this case the basement complex as the source rock of the deposit and make it worthwhile to consider the massive sandstones

of Cambrian and Devonian age as more likely to be the source rock. These Palaeozoic sandstones perhaps hidden in the deeper part of the basin, are exposed in the north-east of the Chad Republic and adjacent Sudanese and Libyan regions. These characteristics are also consistent with the evident south-western supply direction of the terrestrial sediment material and the gradual thickening of the marine layers to the north-east.

Because of the inaccessibility of the area (large uninhabited areas of moving sand and poor water resources), the sandstones of the Nubian facies are still relatively unknown compared with other parts of the earth's surface. It is certain that with serious systematic but relatively modest efforts, much of the missing information could be disclosed.

Hydrogeology of the Nubian sandstone basin

The waters in the aquifers with Nubian facies, equated with Continental Intercalaire in the Western Sahara, are normally of good quality and total disssolved solids content less than 500 ppm is normal.

Among the aquifers with Nubian facies, the so-called Nubian basin is one of the most extensive artesian basins of the world. It covers the north-eastern part of the Sudan, Egypt west of the Nile, the extreme north-east of Chad and south and eastern Libya. In all the basin covers about 1.8 million km^2, and opens towards the north, stretches northward close to the Mediterranean coast. Here the interfingering marine deposits, such as clays and limestones alternate with the remains of the Nubian facies. The stable shelf is separated from the unstable shelf by a rather wide zone with east–west faults. This zone, in which the Qattara depression is situated, forms a transitional zone towards the geosynclinal belt underlying the Mediterranean coast, where the total sediment thickness exceeds 5000 m.

The Nubian basin has a desert surface characterized by extreme aridity. The only pockets of life are located in a series of depressions (100–300 m deep) in the desert plateau sloping gradually towards the north. The most important of these are the oases Kharga, Dakhla, Farafra, Behariya and Siwa in Egypt, and Kufrah in Libya, while Qattara with its extensive sebkha covers an area of 5600 km^2 is uninhabited.

Apart from shallow native wells between 30 and 150 m deep, and the remains of old native wells which witnessed more intensive exploitation of these uppermost aquifers in the past, over 350 wells have been drilled in Egypt since 1959 ranging in depth between 400 and 1200 m. Previously hydrostatic pressure was such that nearly all of both shallow and deep drilled wells were exploited as flowing wells. However, as a result of intensive exploitation of the groundwaters in the depressions by a dense network of wells, decreases of over 30 m have occurred in the hydrostatic pressure, mainly in Kharga oasis.

The underlying basement surface is irregular. It forms isolated outcrops in the Nubian series as far as latitude 29° N, before disappearing completely towards

the north. Basement depth therefore controls the volumes of water stored in these sediments as well as the transmissibility of those parts of the Nubian series which are saturated with water. The basement underlying these aquifers is also important as it controls the intake of the recharge area in the south, which has been more active under past climatic conditions. Towards the New Valley area where the Nubian series are farther away from the basement horizontally and vertically, they are geographically more differentiated (bore-holes here tapped more than 32 water-bearing horizons). The aquifer here is artesian (Himida, 1970).

In the north the Nubian aquifers have a natural discharge in the Qattara depression, by upward leakage through marine overlying beds, which render the seepage water brackish and maintains the sebkha conditions at the bottom of the depression.

As already mentioned, in previous eras the climatic conditions were such that recharge of the Saharan aquifers took place. This has been proved by the carbon-14 (^{14}C) age determinations of deep artesian and shallow groundwaters collected in the Algerian, Tunisian, Libyan and west Egyptian (New Valley) parts of the inner Sahara.

Sonntag plotted the frequency of age determination of the 135 Saharan waters he could locate, against their ages on the basis of the 14 determinations. He obtained the curve shown in Fig. 4. From right to left the broad maximum between 40 000 and 20 000 years BP (before the present) is provided by ^{14}C determination of artesian and deep groundwaters. These groundwaters originate consequently from the last pluvial (Sonntag *et al.*, 1976).

The period between 20 000 and 14 000 years BP which is marked by few age determinations, indicates that in this interval not much groundwater formation took place in the Sahara. The most irregular part of the curve representing the period from 14 000 years BP to present times is interpreted as a post-pluvial humid phase with the humid peaks alternating with arid phases. All the younger waters originate from shallow groundwaters.

Large-scale exploitation of the Nubian-type aquifers

The Kufrah Agricultural Project is a 10 000 ha irrigation development planned to exploit the land and general water resources of an undeveloped desert region in south-eastern Libya. The main objective is the production of sheep through the cultivation of alfalfa by using fertilizers and continuous irrigation over sandy soil. The farm supports over 50 000 sheep. The water field consists of 102 wells which were drilled in 1971 and 1972. Each well is designed to produce 76 l/sec and to irrigate 100 ha. The distance between each well is 1130 m, and each is fitted with a self-propelled sprinkler which rotates over 100 ha in 60 hours.

Originally the piezometric configuration indicated a slight gradient of 0.3 per cent towards the north-east. This could be explained either by a slow emptying of the groundwater reservoir through very far outlets in the north-east, or by a present recharge occurring in areas located far away to the south. What is certain

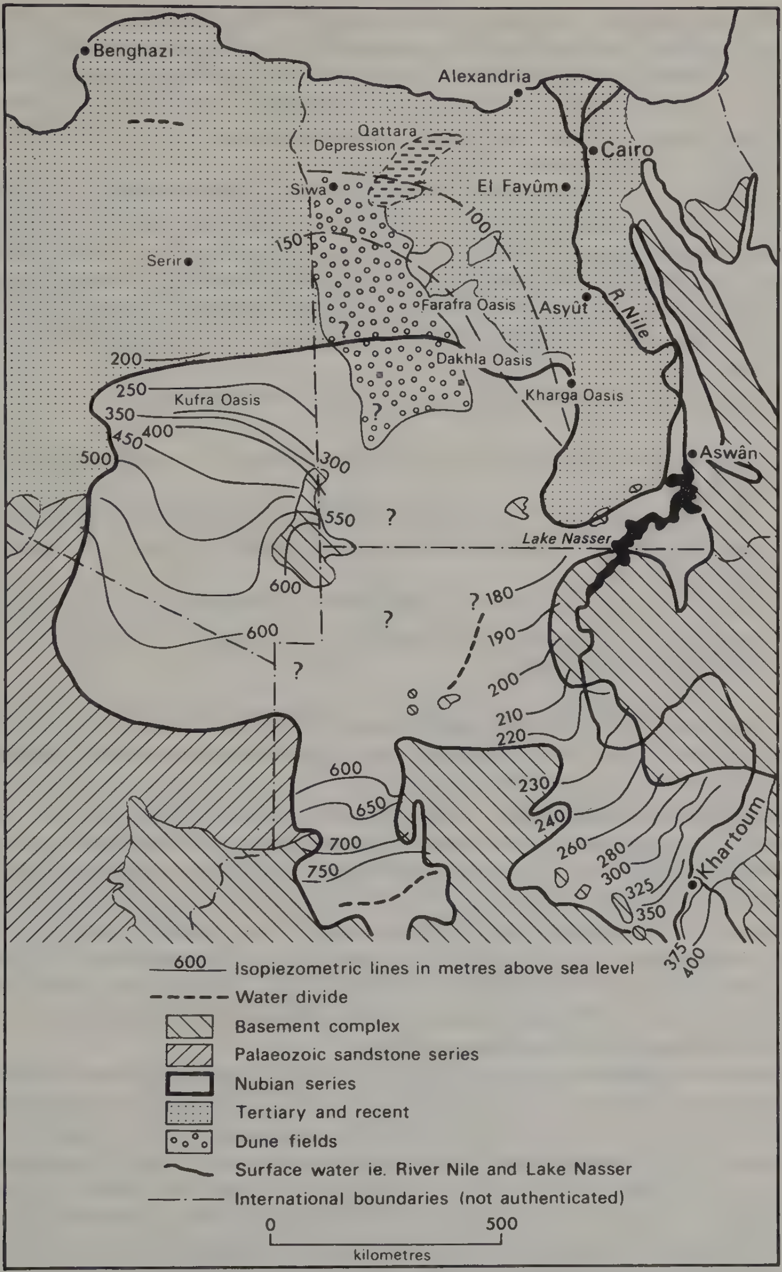

Fig. 4. Isopiezometric lines at the north-east Sahara.

is that groundwater in Kufrah can be drawn only from storage. Although there are two aquifers, one shallow and one deep, the production wells draw water only from the deep one, which in its turn produces a vertical drainage from the shallow aquifers (Burdon, 1976). This is well illustrated in Fig. 5 by the time–drawdown graphs of some observation wells on piezometers under the influence of the Kufrah well-fields since July 1972.

A mathematical model was built in order to predict the response of the water table on water withdrawal over 40 years at a total rate of 4.3 m^3/sec. The resulting drawdown computed in this way was 20–36 m over an exploitation period of 40 years. In February 1974, when 61 wells were operating and producing a total discharge of 4 m^3/sec, drawdowns were measured ranging from 5 to 15 m in little more than one year of exploitation. This was higher than was predicted.

The following conclusions can be drawn from this example:

1. Apparently the important groundwater development was based on wrong assumptions.
2. The prediction made by a model is reliable only if the instrument has been calibrated and controlled over a past known period of time of not less than two years.
3. Any important groundwater development should be preceded by two years (at least) of pilot experimentation on a significant scale (1000 ha as an example in this case).

In December 1975, the production reached 5.1 m^3/sec through 79 operating wells. Because of the large differences between horizontal and vertical permeabilities related to the horizontal layering of the strata, there exists a higher resistance to the vertical flow component than to the horizontal flow component of the groundwater movement. It happened that the clay layer separating the shallow waters from the deep waters, acted as an impermeable layer on sudden changes in the waterlevel of the deep aquifer, but as a relatively permeable layer on a lowering trend of long duration. This characterizes the aquifer under consideration as a so-called 'leaky' aquifer. As a consequence, it takes a long time before the entire aquifer is activated by the large-scale water withdrawal from the partial penetrating water wells, which nevertheless provoke pronounced local vertical pressure gradients.

The time–drawdown curves of Fig. 5 of the piezometers all show a decrease in the rate of drawdown of the water-level of the deep aquifer. In case of piezometer P13, even a compensational effect can be observed. The irregularities of the graphs reflect the influence of the complex variations in the discharge of the well-field. The surface waters on the other hand show a slow but steady decline in water level. For this reason, the general examination of the aquifer based on the situation observed during February 1974 was more pessimistic than the examination based on observations of December 1975. In December 1975, the stabilization of the water-level decline was probably the result of the reaction of the

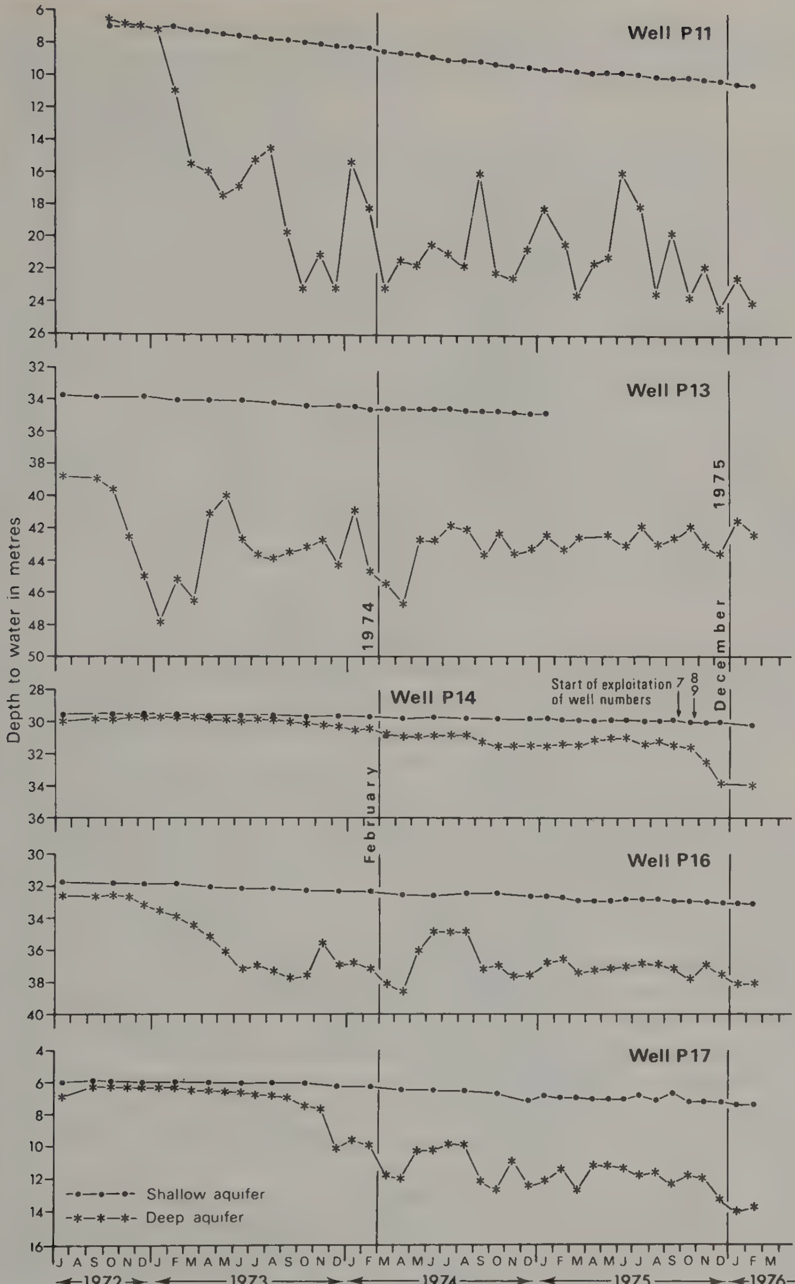

Fig. 5. Time–drawdown curves of some Kufrah observation wells.

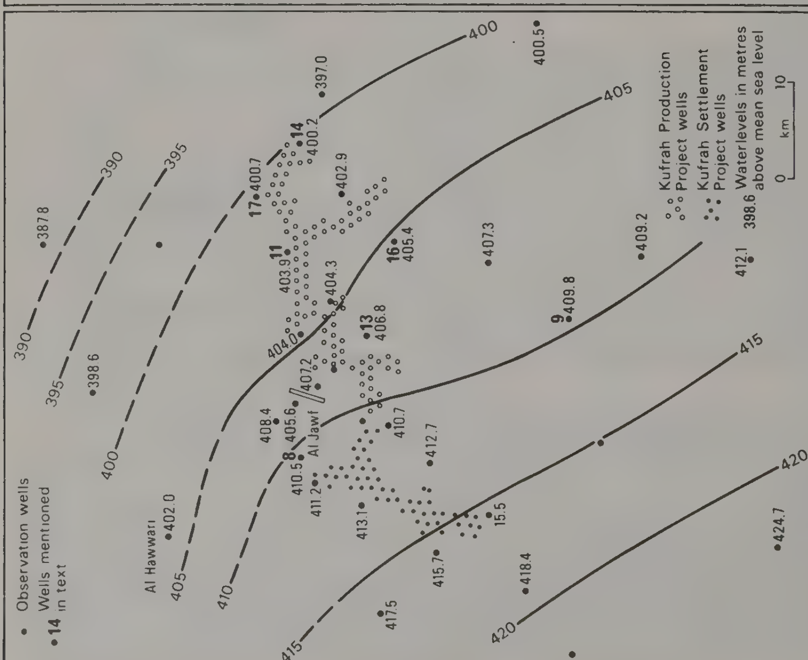

Fig. 6. Initial state of piezometric contour lines of the deep aquifer at Kufrah, south-east Libya, before pumping in 1972.

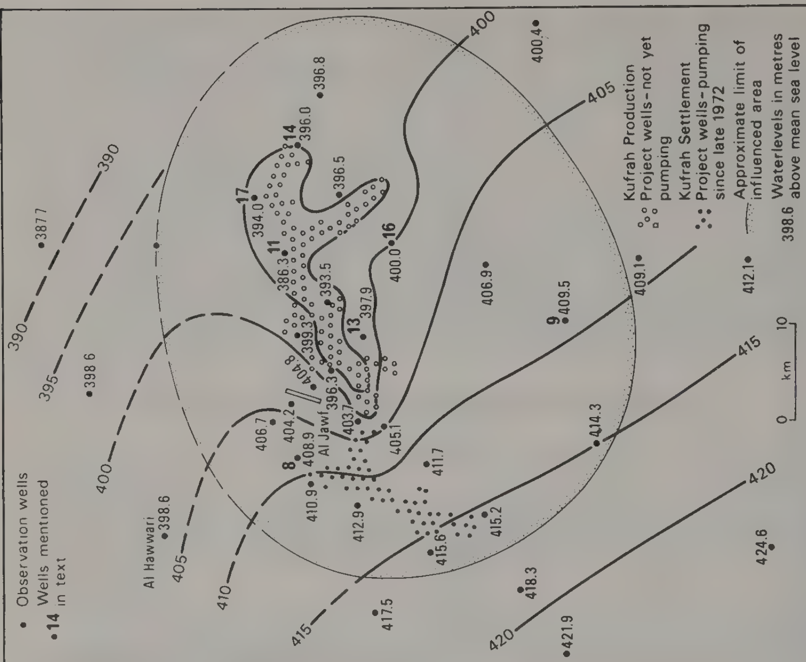

Fig. 7. Piezometric contour lines of the deep aquifer in December 1975 after three years of pumping.

aquifer over its entire thickness in the area indicated on Fig. 7 while this situation had not been reached in February 1974 (Fig. 5). As a result the transmissivity values, based on 24-hour pump tests executed in the past, are on average 23 per cent too low (Schoute, 1976).

By now longer series of observations make an improved hydrological model study possible, and should give much more accurate prediction. Because of the mutual influence of the discharge wells, each well should be represented in the new model. Thus far, discharges could be reconstituted only globally as they were not continuously recorded, but were measured only once a month, and the most reliable deduction was that the discharge should have satisfied the current intensity and frequency of irrigation, according to the water demands of the crops. Since flow-meters are sometimes defective, the discharge recorders which were to be installed from the beginning of 1976 should facilitate and improve the interpretation of hydrogeological data. With the new model, former predictions should be checked such as the prediction made that at some places the pumping water levels are likely to be lower than the screens within ten years.

Continued exploitation of non-renewable resources even in places with large groundwater reserves will require ever-increasing efforts towards rational management. In some cases the economic constraints are felt earlier than in others and depend on the economic reserves of the financing agency, which in the last resort will be the country in question.

It will be clear that important additional investments will have to made in order to allow the Kufrah project to continue on the present scale. Much depends on the decline of the water level as a function of the project's water discharge. This economic loss represented by the decline in water level should be compensated as well as possible by the agricultural production. Therefore, emphasis should be given to a high water-use efficiency (Schoute, 1976).

In the Kharga and Dakhla oases of New Valley in Egypt, approximately the same development took place. Only economic constraints forced a limit to be placed on land reclamation when water levels, mainly in Kharga, dropped more quickly than predicted. Although 1 500 000 feddans were planned for cultivation, in reality cultivation has never exceeded 50 000 feddans. An attempt should be made to increase the cultivated area by more efficient water use. Since 1959, almost 100 million Egyptian pounds* have been spent on the entire area, 32 million of which was by regional government agencies. Annual running costs have been £E 7 million during the last years. This justifies largely the extra investments to be made in order to control the ongoing wastage of valuable high quality groundwater. For one thing is certain the New Valley can house more inhabitants (at present 100 000) and produce more agricultural produce than it does today.

The Kufrah production project is likely to have cost about Libyan dinars (LD) 30 million† up to 1974 and annual running costs are estimated at LD 10 million (Allan, 1975).

* Value of the Egyptian pound (£E) about US dollar 2.56. (1976).

† Value of the Libyan dinar (LD) about US dollar 3.15 (1976).

Scattered small-scale exploitation of the Nubian-type aquifers

In order to open the vast uninhabited desert areas and make them accessible, where possible, to economic development of their mineral, land and livestock resources, a road network has to be established. For road construction water is required and the only available source in this case is groundwater. In Saudi Arabia, for example, the construction of the new vast network of major and secondary roads has necessitated the drilling of numerous boreholes and the development of groundwater which would at first meet construction needs, and afterwards supply rest houses and small settlements springing up along the arterial roads.

A UNDP project has studied the technical feasibility of a Trans-Saharan road (REM/71/251) joining Algeria, Mali and Niger, to open up this part of the Sahara, to introduce tourism and also to allow the development and export of mineral resources and of the products of the local population including handicrafts. The estimated rate of return on the necessary investment to construct the road was higher than was originally expected. Nevertheless, the project has reached a second phase and the drilling of the necessary water wells has started along certain parts of the road.

For a long time the Sudan and Egypt have been discussing the construction of a road from Kharga to the north of the Sudan. During the second Regional Meeting on the Nubian Sandstone aquifers, it was recommended that the necessary boreholes be drilled for the road with sufficient care in order to make them useful also as hydrological exploration wells for the Nubian aquifer studies. Further recognizing the fundamental necessity of a series of exploration holes between Darfur in the Sudan and Kufrah in Libya in order to understand the transmission and storage capacity of the Nubian aquifers, such holes would at the same time enable the Sudan and Libya to open an overland communication between the isolated but relatively prosperous province of Darfur, and the new development centre in Kufrah.

The road network would also justify the exploitation of known but isolated mineral deposits, and new explorations from this communication system would be facilitated. Water would be needed for mineral exploitation and the establishment of small control, fuelling and trading posts, where passengers, truck drivers and nomads may find fresh provisions.

The so-called water-yard Er Rwakeel, 40 km south-west of Khartoum, could be a model for such a desert post in the future. Here two wells each pumps 35 l/sec from the water table about 90 m deep, to the surface, for the irrigation of 32 feddans and the watering of the cattle. On the irrigated plots wheat, fodder, vegetables and citrus are grown. The water is sold for 0.2 piastres for 30 litres (the content of a sheep's skin). A poultry farm also supplies 600 eggs per day, sold for 32 piastres a dozen, and an average of 5 kg of cheese are manufactured a day to be sold for 55 piastres/kg.

If a rest-house could be added and also a solar energy plant, to provide energy for pumping,* cooling, lighting and food conservation, then such posts built

alongside an international road could be economically self-sufficient. They could provide a most efficient use of the Nubian sandstone waters without creating those problems existing in Kufrah or similar groundwater developments.

Results of the UNDP/UNESCO north-western Sahara project (UNESCO, 1972)

Another case is the study of the water resources in the north-western Sahara, covering Algeria and Tunisia south of the Atlas ranges, over an area of 800 000 km^2. This was carried out by the UNDP/UNESCO project 'Reg 100' during the period from 1 November 1968 to 30 June 1972. The objective of the project was to determine the best conditions for the exploration of the enormous groundwater resource. This project clarified the role of the present recharge with respect to the total water balance of a large Saharan basin, in this case the western Sahara. This basin was studied in detail by the project UNDP/UNESCO, 'Reg 100' (UNESCO, 1972).

It should be noted that this complex aquifer still has a significant present-day recharge compared with the other aquifers. It can be divided into three major units:

Aquifer of the Continental Intercalaire
Aquifer of the Complex Terminal
Coastal aquifer of South Tunisia

Aquifer of the Continental Intercalaire (*CI*)

Main aquifer characteristics:

Area of extension over 600 000 km^2.
Effective thickness from 0 to over 1000 m with an average between 250 and 600 m.
Porosity generally between 22.6 and 28.7 per cent with assumed effective porosity of 20 per cent.
Permeability varies from 1 to 10×10^{-5} m/sec.
Transmissivity varies from 1 to 50×10^{-3} m^2/sec.
Total dissolved solids content is from 1 to 6 g/l with an average of 2–3 g/l.
Very deep aquifer providing water with temperatures up to 80°C and high artesian pressure except along marginal zones where recharge still takes place.

Measuring campaigns carried out in 1932, 1949–50 and 1959–60 have shown that the yields of the foggaras have not changed. They can be considered as constant.

The first boreholes were drilled at the end of the last century. The number of boreholes was afterwards increased gradually until, from 1950 to 1960, the

*In the meantime two French solar pumps (SOFRETES) have arrived in Sudan to be tried out under severe and arid circumstances.

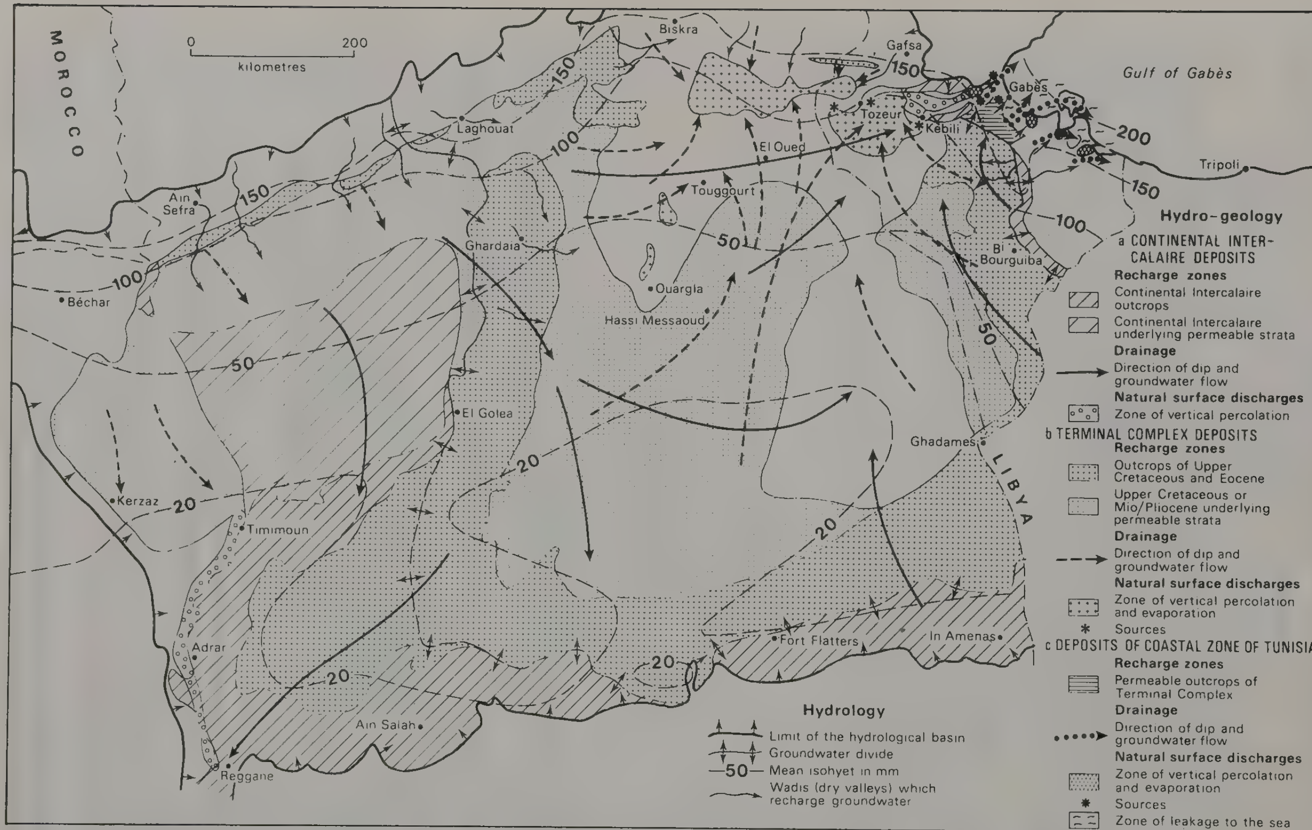

Fig. 8. Hydrology and hydrogeology of the northern Sahara of Algeria and Tunisia.

Source: UNESCO, 1972, 'Etude des ressources en eau du Sahara Septentrional', UNESCO/UNDP Project 100.

groundwater exploitation accelerated suddenly. After recovery, levels did not revert again to the initially observed water levels. The water levels very slowly started to fall in the regions of groundwater development. A stationary regime became a non-stationary regime around 1956. Parallel to this history, the aquifer was tested in a steady-state model valid for the period until 1956. All new water exploitations since, either under free-flowing or pumped regime were individually introduced in a second time-dependent non-steady-state model, in which the fluctuations in exploited yields in the different periods between 1956 and 1970 were simulated. These exploitations resulted in drawdowns, which can be observed and measured in the field and should appear in the model in a corresponding way.

On the basis of a water balance established during more than two years of calibration of diverse hydrological models, accompanied by continuous control in the field, the findings shown in Table 5 were obtained.

Considering the fact that outflow towards Tunisia and upward seepage have remained practically unchanged, the increase of exploitation of groundwater of 2.7 m^3/sec through a great number of boreholes, some of them 1500 m deep, in the period from 1956 to 1970, has come alomst entirely from storage and has been manifested in the lowering of the water table or water-pressure levels.

Table 5. Water balance of the Continental Intercalaire in units of m^3/sec

	1956	1970
Input		
Recharge through infiltration of runoff water from the Atlas mountains and others; Infiltration of exceptional heavy rains on the Grand Erg Occidental directly overlying CI	8.5	8.5
Output		
Subsurface outflow towards south Tunisia	3.6	3.6
Vertical upward seepage feeding the chotts	0.9	0.8
Groundwater exploitation: foggaras, developed springs (before feeding the sebkhas in the south-west), and borehole	4.0	6.8
Total	8.5	11.2

Aquifer of the Complex Terminal

Some aquifer characteristics for orientation:

Area of extension is about 350 000 km^2.

Depth of aquifer generally from 100 to 400 m, except a deep trough reaching to 2000 m depth, immediately south of the Atlas.

Water quality from 1.5 to 6 g/l, with an average of 4 g/l. A summary of the water balance for the Complex Terminal is found in Table 6.

Table 6. Water balance of Complex Terminal in units of m^3/sec

	1950	1970
Input		
Recharge along the marginal mountainous zones		
Infiltration of exceptional rains on the Grand Erg Oriental feeding the underlying Complex Terminal	18.5	18.5
Output		
Vertical upward seepages evaporated in the sebkhas and feeding the chotts	10.0	8.9
Exploitation by boreholes and developed springs	8.5	12.6
Total	18.5	21.5

As the aquifer is more easily exploited by boreholes than the deeper aquifer of the CI, the non-stationary phase of the steadily falling water table and water-pressure levels had been reached as far back as 1950. Practically all wells have to be pumped.

Again, it can be seen that from the increase of 4.1 m^3/sec, groundwater exploitation between 1950 and 1970, 3 m^3/sec, have been drawn from storage.

Coastal aquifer of South Tunisia

This aquifer is completely isolated from that of the Complex Terminal but is fed by the aquifer of Continental Intercalaire.

This aquifer is artesian over its full length along the coast up to 10–20 km inland (total area of extension about 3000 km^2). The aquifer is 100–200 m deep; water temperature 25°C, with higher temperature along the El Hamma fault (40–50°C); and total dissolved solids content of 3–4 g/l. However, the salinity increases towards the north-east and towards the south-east (about 8 g/l). The water balance is summarized in Table 7.

The total amount of water reserves stored in the three above-mentioned aquifers is estimated to be $6 \times 10^{13} m^3$. This volume could supply a hypothetical continuous discharge of 1000 m^3/sec for 2000 years. From this point of view, exploitation could be increased in the future without any short-term harmful effects. In practice, however, the water table will go down continuously at various rates, depending on the locality and the intensity of pumping.

The drawdown will be maximum in the larger centres of water withdrawal and zero in certain areas far away from points of water extraction.

From the increased groundwater exploitation of 0.9 m^3/sec between 1950 and 1970, 0.5 m^3/sec is drawn from storage.

Table 7. Water balance of the coastal aquifer of south Tunisia in units of $m^3 sec$

	1950	1970
Input		
Recharge along the marginal mountainous zones from occasional runoff and rain water	2.6	2.6
Recharge from the aquifer of the CI	3.6	3.6
Total	6.2	6.2
Output		
Vertical seepage (evaporation) sebkhas	0.3	0.3
Seepage into the sea	2.7	2.3
Exploitation by mainly artesian boreholes and springs	3.2	4.1
Total	6.2	6.7

Factors determining the cost of water

The lowering of the water table has a number of economic effects. New investment is required for further or deeper boreholes, which will often be associated with higher pumping costs, leading to increases in the cost of water per unit of volume.

From this point of view the lifetime of a borehole is a very important parameter and is the main determinant of the cost of water. For instance in 1976 a borehole costing 2000 Algerian dinars or about 200 Egyptian pounds, supplying 100 l/sec, provides water for a certain cost depending on the lifetime of the borehole in the following way in lithological conditions commonly encountered in northern Africa.

From Table 8 it is clear that boreholes should be constructed with a minimum lifetime of 20 years.

In Algeria and Tunisia this pattern applies only to those boreholes which are less deep, with the exception of those in the region of Zarzis in Tunisia. However, the deep boreholes capturing water from the Continental Intercalaire have all presented problems, either during their construction or during their exploitation, which in the case of the oldest started as early as 1956.

The difficulties encountered were as follows:

(a) Because of the great depth of such wells high-quality construction materials, pipes and screens must be specified such as are rarely used for water wells.

(b) The presence of other aquifers, some possibly very saline, which must be perforated in order to reach the exploitable aquifer, can present problems if the isolation of saline water is not carried out in an appropriate way. Well casing and equipment deteriorate if saline waters enter the system.

Table 8. The relationship of water costs and well-life

Lifetime borehole (years)	5	10	20	30	50
Cost of 1 m^3	16.0	9.5	6.5	3.6	5.2*

*In 1/100 Algerian dinar = cents or 1/1000 Egyptian pound = millimes.

(c) Pressures at the surface can reach 27 kg/cm^2. In such cases rapid closure of the well can cause internal over-pressures (water hammer effect) which can destroy the vertical tube system at the delicate pipe junctions or well screens.
(d) High artesian yields, varying between 200 and 400 l/sec produce very high water velocities in the well screens causing mechanical destruction and vibration, leading to destruction of the concrete setting.
(e) The chemical composition of the pumped water influenced by the increasing CO_2 content through the pressure release and rapid cooling during its vertical transport to the earth's surface may cause corrosion.

Criticism of the method of execution of the borehole is normally the result of retrospective hypothetical reasoning, after an accident of some sort has caused the destruction of the well. For this reason efforts have been made in the UNDP/UNESCO West Sahara project to find out what is actually happening in the boreholes by means of photographic inspection. After many years of trials it has become evident that proper construction of a borehole is the most important condition to assure a long life for a water well. Corrosion is the next most serious problem.

Economic calculations have generally been based on the assumption that the lifetime of a deep hole should be 20 years, and that of wells not exceeding 1000 m should be 30 years, with the exception of the wells on the Zone Djerba Zarzis, where the lifetime has been taken as 20 years because of the highly corrosive quality of the water.

Specific advantages of regional studies of Nubian Sandstone Basin (see Fig. 1)

Returning to the Nubian Sandstone Basin, the UNESCO experience, gained in other parts of the Sahara, could be used to make an adequate regional study of the basin, in which all available data should be systematically collected, compiled and synthesized. Certainly local problems like the water management of the New Valley oases (Kharga and Dakhla) and Kufrah would profit from the results of such a regional study. A regional study would probably provide more basic criteria for the determination of hydrogeological boundary conditions for more localized projects. It should trace the main impermeable barriers (basement uplifts), if any exist unnoticed, under the rather monotonous desert crust con-

sisting of Nubian or younger deposits. The base depths should also be explored as these data would in the first place allow an approximation of the storage and transmission capacities for groundwater in the Nubian complex.

It is known that groundwaters in the western part of the basin reach much higher levels than in the eastern part near the Nile and Lake Nasser. (See the appropriate water-level values above sea-level in Fig. 2.) North of Darfur just south of the 18th Parallel groundwater reaches 600 m above sea-level and the piezometric surface slopes gradually to the north. On the Chad–Libyan border, the groundwater table has the same level and grades towards Kufrah in the north-north-east, where the water table lies around 400 m above sea-level (see Fig. 4). North-east of Kufrah over a relatively short distance the water table drops to 250 m above sea-level near the intersection of the Libyan–Egyptian border at the 25th Parallel, that is at roughly the same latitude as Kharga.

Although the region south of the 25th Parallel, where Nubian Sandstone forms the desert's surface, slopes towards the east, no parallel equi-piezometric lines could be drawn in a north–south direction, indicating groundwater flow in the direction of the slope, over any significantly extensive area on the basis of water levels observed at sparsely scattered watering points. On the contrary, it was observed that the Nile south of Aswan recharges the Nubian aquifers. Such recharge takes place, as already mentioned, along the shorelines of Lake Nasser north of the Second Cataract, now inundated by the lake, but also upstream in those sections of the Nile where the river cuts its valley into the Nubian Sandstone formations between the Third and Fourth Cataracts.

West of Dongola, the water table reaches 227 m above sea-level and grades down to 180 m above sea-level west of Wadi Halfa near the Egyptian boundary. It cannot slope much further in this direction since Lake Nasser/Nubia has had a water level of around 175 m since October 1975.*

It is, therefore, suggested that there might exist a buried sub-surface basement uplift or dike system, which connects the basement complex of Kordofan with the basement barrier separating Lake Nasser from Kharga oasis. Such a threshold could prevent the water table from having a more pronounced slope in an easterly direction. What is known is that there exists a series of small basement outcrops south of Kharga approximately coinciding with the 24th Parallel (which may branch off from the wider previously suggested basement uplift continuing to the south). An aeromagnetic survey proved that this barrier reaches up to 28° E.

This survey was carried out in order to observe the hydrological boundary conditions along the southern border of the New Valley area, where a project is currently being executed by FAO. The sub-surface continuation of this barrier, west of the basement outcrops to 28° E longitude, could already be predicted on the basis of an extensive diatomite deposit with an area of about 1000 km^2, which has been attributed to a dried-up lake which existed during the

*This opens interesting perspectives for a rather large area which could be afforested with trees which draw their water from about 10 m depth.

Mousterian period. From this period date also similar lake deposits from the Chad basin, which then extended over a larger area than at present (Faure, 1969). Results of aeromagnetic surveys in the north-west Sudan revealed that a major, well-defined sub-surface channel could be traced from the Mourdi Depression between the Palaeozoic Ennedi and Erdi highlands in north-east Chad. This channel of about 20–30 km wide, verified by borings in the Sudan, swings from an east–west trend to follow a north-easterly direction towards the Egyptian borders, between 27 and 28° E (Country Review, 1974). As a first approximation, the quantity of groundwater stored in the channel has been estimated at 10^{11} m^3. This is based on a storage capacity of $15–25 \times 10^{-2}$. The relatively high transmissibility of this channel possibly speeds the flow of groundwater to the artesian Nubian aquifers exploited in the New Valley. This, taken together with the existence of the relatively impermeable west–east barrier, which continues in a north-eastward direction between Lake Nasser and Kharga oasis could explain the much quicker groundwater decline in Kharga than in Dakhla.

In the case of a regional project, our supposition with respect to the hydrological situation could be checked by an aeromagnetic survey which should not stop at 28° E, but should continue at least to 25° E, where the basement again reaches the surface. Such a survey, covering a much more essential part of the Nubian sandstone basin than could be justified for the New Valley project (between 28 and 29° 30′E), would greatly assist the latter project. To what extent the Kufrah basin could be linked with this system is unknown and needs clarification.

Of course groundwater extraction in Kufrah will never influence groundwater extractions in the New Valley, although the sphere of influence marked on Fig. 7 for the Kufra project in December 1975 is expected to increase gradually. It is, therefore, strongly recommended that projects of groundwater development of the size of the Kufrah project should be separated by a distance of at least 50 km in the Kufrah area. Such minimum distance criteria have also been developed for the New Valley groundwater withdrawal schemes. The optimum distances should ultimately be decided on the basis of a careful comparison of the aquifer parameters.

The valuable experience gained as a result of initiating the ambitious and expensive groundwater development schemes in the similar but sometimes contrasting environmental and economic conditions of Libya, Egypt and Sudan provide general guide lines for groundwater exploration in the entire area as well as indicators which should lead to the avoidance of mistakes. Such experience should be brought to bear on the problem of the natural discharge point of the Nubian sandstone basin in the Qattara depression. With respect to the ongoing exploration of the Qattara depression for electric power generation consideration should be given to the effect of the change in hydrostatic pressure resulting from the flooding of the depression.

Another matter requiring investigation is the relationship of the Qattara depression and the Nubian waters. It is argued that an increase in the hydrostatic pressure in the Qattara depression of 2.5 kg/cm^2, corresponding with a rise of

about 20 m in the new lake level (assuming a saline evaporation-residue of specific weight varying from 1.15 to 1.25, being the specific weight of Dead Sea water) could considerably reduce the outflow of Nubian seepage waters.

Taking into account the estimation of the natural discharge of the Nubian aquifer into the depression as 3 000 000 m^3/day or 35 m^3/sec, the reduction of outflow may be perhaps of the order of magnitude of the water withdrawal now taking place in the Kufrah project.

Artificial recharge

The ancient Jessour and Meskat systems

Recognizing the high toll which is paid for surface storage under arid and semi-arid conditions, artificial recharge should be considered as a welcome alternative. Once the water is underground, it cannot remove the fertile soils or cause inundations while it is well protected against evaporation. Artificial recharge is defined as augmenting the natural replenishment of groundwater storage by some method or construction for the spreading of waters, or by other artificial changes in natural conditions.

The best way of supplying water near the surface within reach of plant roots, which means it is also available for evapotranspiration and not for direct evaporation, was obtained by so-called rainwater harvesting which was developed 4000 years ago. On the rocky and impermeable slopes of catchments, the scarce rainwaters were carefully collected in small drains and conducted to the valley bottom. Here the alluvial deposits which have already accumulated, had to be cleared of large stones. Transverse small dams, nowadays planted with unpalatable bushes, oppose eventual runoff and encourage infiltration in the valley infill where these runoff waters can be stored (Jessour) (Fig. 9). Plants that become dormant during dry periods and begin growing when water becomes available are particularly suited for this type of runoff agriculture intensively applied in Tunisia (Ad Hoc Panel, 1974).

In undulating plains, without any visible drainage pattern, micro-catchments are used, each surrounded by a dirt wall of 15–20 cm high. At the lowest point within each micro-catchment, a basin is dug about 40 cm deep and a tree is planted. The basin stores the runoff from the catchment. The basins are fertilized with manure, and, unlike the catchment area, their soil is kept loose to encourage water penetration. In this way deep-rooted drought-resistant fruit trees like almond and olive trees can be grown on micro-catchments ranging in size from 16 cm^2 to 1000 m^2, depending on the rain which may be expected and the water needs of the adult tree (Figs 9 and 10). Through these agricultural methods practised at Jessour and Meskat, based on painstaking water management, old cultures such as the Nabatean, Carthaginian and others could cope with the constraints imposed by aridity.

Two thousand years ago parts of northern Africa, under climatic conditions not essentially different from those of today, became the granary of the Roman Empire (Combe, 1974). At present large-scale remains can be seen of cisterns

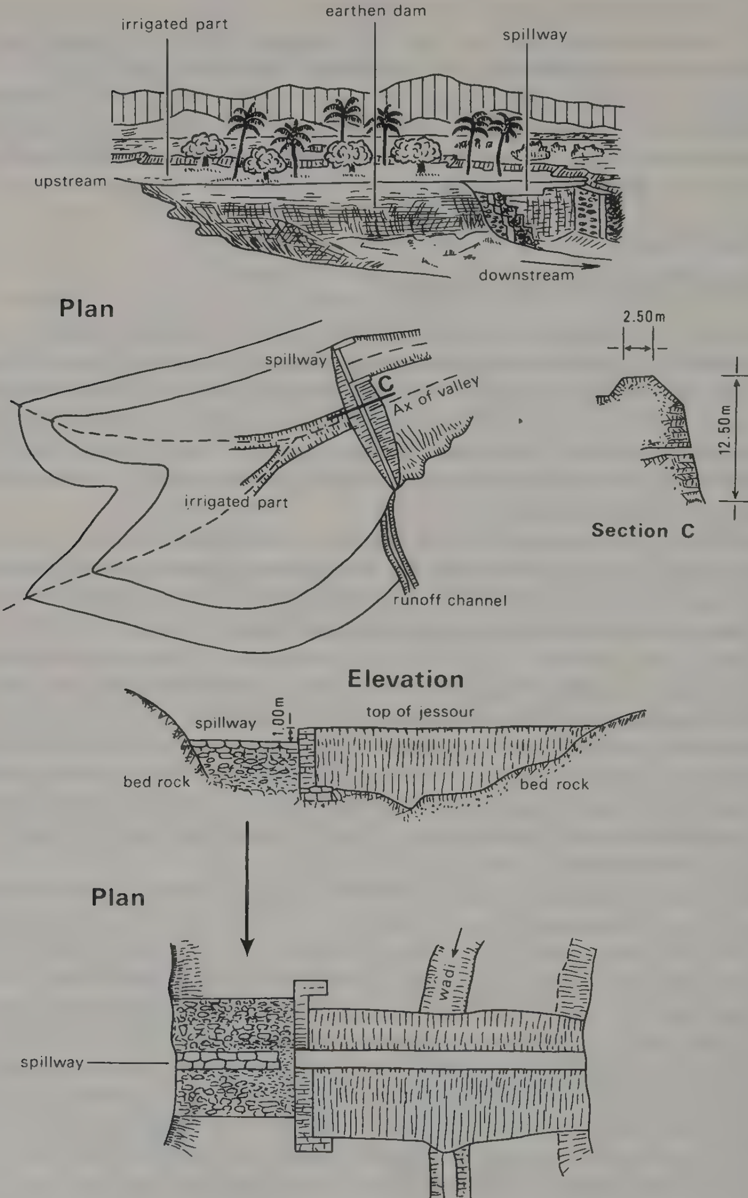

Fig. 9. Prototype of a Jessour at Beni-Ceguiane (Matmata) 1926.

Source: Fitouri Centre de Recherche, Genie, Rurale, Tunisia, courtesy M. S. el Amami.

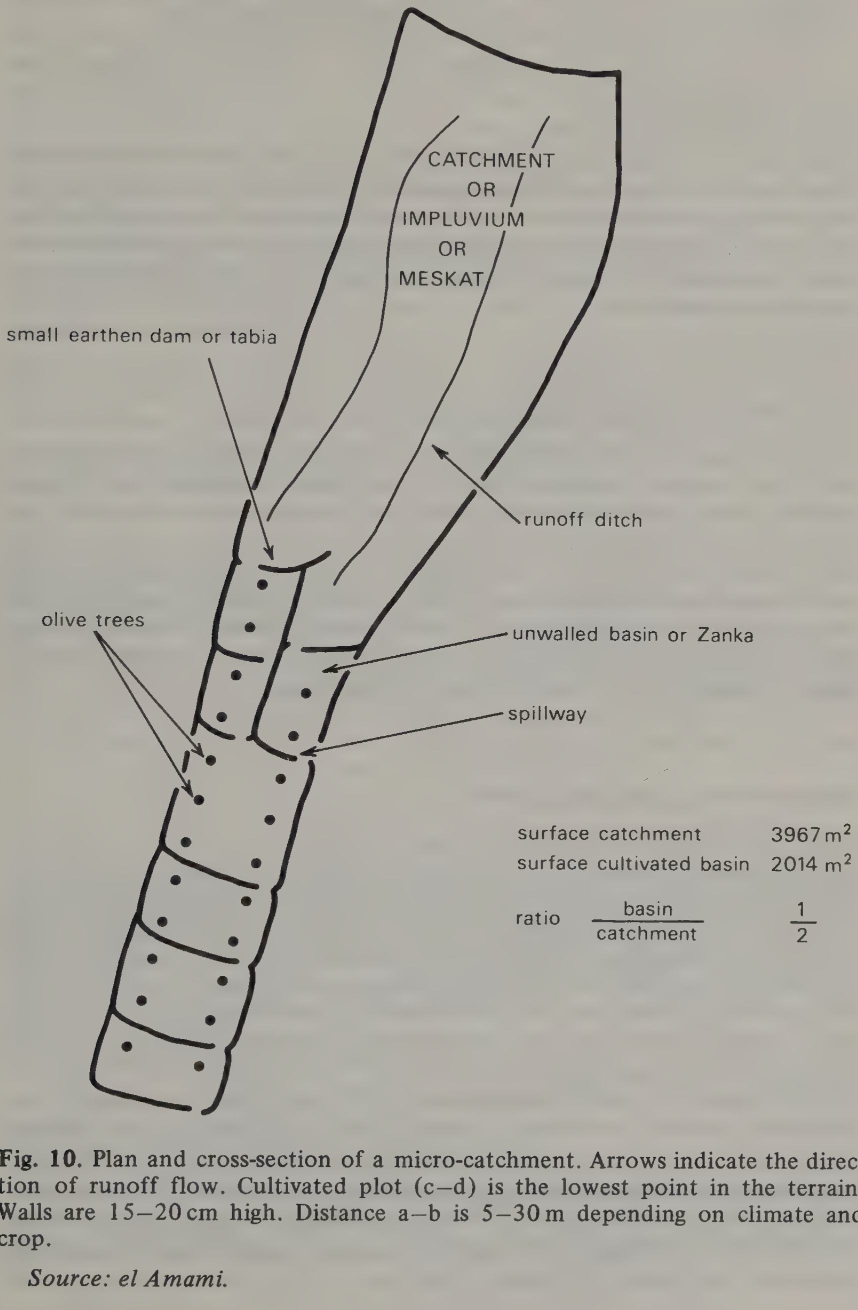

Fig. 10. Plan and cross-section of a micro-catchment. Arrows indicate the direction of runoff flow. Cultivated plot (c–d) is the lowest point in the terrain. Walls are 15–20 cm high. Distance a–b is 5–30 m depending on climate and crop.

Source: el Amami.

and agricultural systems described above which have recently been studied by scientists in order to rediscover the underlying scientific principles.

Underground barrages

In the massive alluvial deposits of valleys eroded into impermeable bedrock, the principle of the underground barrage can be introduced. This construction will lift the deep water table to the root zone, or to the level reached by the local wells, and increase underground storage upstream of the barrage. Such constructions were executed in the early fifties (Gignoux *et al.*, 1955) in Morocco near Tiznit in the Oued Marra.

Flood spreading over permeable surfaces

In Saudia Arabia shallow aquifers in wadi alluvium, draining towards the Red Sea, lie on basement volcanic rocks or impermeable sediments. The wadis are relatively steep and groundwaters forming in them move downstream at a relatively high rate. Particularly in the southern Tihama region, these valleys supply flood waters debouching from the hills, and spread out over piedmont deposits and outwash fans, to flow over the coastal plain. A simple but ingenious method of flood diversion, like the dam built at the Malaki site on the Wadi Jizan, spreads the flood waters over wide areas where infiltration is facilitated, increasing soil moisture and contributing to groundwater storage.

Problems related to artificial recharge

The problem of the recharge of excess surface waters is that these waters should be again available when needed, at minimum costs. The quality of the waters should not deteriorate but even if possible improve. Therefore groundwater reservoirs depleted by over-exploitation in the past may be very suitable. Generally the hydraulic characteristics of such aquifers are known, and abandoned well-fields are available either for the injection of recharge waters or for the withdrawal of groundwater. Where high surface permeabilities allow high, and thus economic, infiltration rates, feeding these abandoned well-fields, should be considered for artificial reactivation.

From a hydraulic point of view, pumping and recharge rates of the same borehole should be equal. In practice, however, recharge rates seldom equal pumping rates. Differences are due to clogging surrounding screened portions of the borehole. In general clogging rates are proportional to the suspended material in the recharge waters. However, other effects can also lead to clogging, such as entrapment of fine aquifer particles, air bubbles, and chemical reactions between recharge and natural waters (Chow, 1964).

Examples of recharge projects or proposals

The water supply of Tanger. The city of Tanger in north Morocco is provided with municipal water from the Charf el Akab groundwater basin. From the beginning of the exploitation in 1933 the water table decline has been 17 m. In 1956, after some trials of water injection, recharge was seen as a solution, using the flood waters of the Oued Miharar.

After decantation the water was treated. The recharge is carried out by spreading the recharge waters over a series of consecutive basins. The total infiltration rate reached 370 m^3/hour. With the help of a mathematical model the groundwater response has been studied, simulating an increase of recharge on the basis of existing hydrological data. The results of this study have shown the possibilities of increasing the output of this system by recharging the otherwise wasted flood waters of Oued Hachef in order to satisfy the needs of the growing city until 1985. Most important, however, is the relatively low cost of this form of water management in this case in that the waters produced by this complex system cost four times less than the construction of a dam for surface storage would have cost (Combe, 1973; Comité Maghrebin, 1973).

Grombalia groundwater reservoir – Tunisia. In Tunisia various methods of recharge have been tried for the over-exploited groundwater storage in the region of Grombalia, south-east of Tunis, where the water table went down 5 m in ten years. Methods of recharge compared included the injection through abandoned wells, infiltration through basins, and spreading of controlled yields over permeable portions of the wadi bed. The latter method seems to be the most effective for large-scale recharge, with part of the recharge waters being decanted as they originate from surface storage reservoirs (Ennabli, 1971).

East Bank Jordan valley. Artificial recharge has also been proposed and studied on the east bank of the Jordan valley in the Karameh–Rama area. Here excessive groundwater withdrawal for irrigation, in an area covering the previous alluvial fans of several confluent wadis of the Jordan river, created a pronounced decline in water levels. In the dewatered area (about 130 km^2) the groundwater quality deteriorated from 1000 to 4000 ppm. The following water balance elements were found:

Recharge	35.22×10^6 m^3/annum
Discharge	47.27×10^6 m^3/annum (mainly pumped water supplies for irrigation)
Deficit	11.94×10^6 m^3/annum

The recharge could be supplied by the above-mentioned wadis besides the excess irrigation returns and canal losses. The recharge proposal involved the conveyance of part of the Yarmouk river flood waters, through the East Ghor canal, which should be extended over 15 km for this purpose.

The objectives of the recharge project were defined as follows:

1. Replenishment of the aquifer in the area concerned.
2. Prevention of aquifer destruction and water quality modification, through induced hydrostatic pressure control.
3. Seasonal storage of excess waters to meet the needs of the months with peak demands.

The recharge was planned to be supplied by spreading over shallow excavation in the alluvial fans after having percolated through sand filters in concrete basins. The dry season, when no recharge is applied, could be used for the cleaning of the sand filters and for maintenance. Installation costs in October 1972 were estimated to amount to 150 000 Jordanian dinars.

Water supply of the Algiers region. The region of Algiers obtains its municipal irrigation industrial waters from the Mitidja plain. This plain is enclosed between the Mesozoic Atlas Tellien (reaching 1600 m above sea-level) and the anticlinal fold of the Sahel ridge which reaches 260 m above sea-level and on which the city is built.

The Mitidja plain overlies an important groundwater reservoir which has its outlet to the Mediterranean where the Sahel ridge shows a breach between the city and Cape Matifou. Here a narrow littoral separates the plain from the Mediterranean. The mathematical model made of this groundwater reservoir showed an overall groundwater flow towards the sea of $14.3 \times 10^6 \, m^3$/annum for the simulated conditions of the hydrological year 1971–72 when the total water use was about $300 \times 10^6 \, m^3$.

The estimated needs for water for the entire Algiers region in the year 2000 will be $970 \times 10^6 \, m^3$. Additional storage reservoirs in the Atlas hinterland will be built and actual wadi discharge into the sea will be utilized to meet future needs. However, the first of these reservoirs and diversion works will not be completed before 1980.

Consequently the groundwater reservoir, as the only available reserve, will face a period of over-exploitation between now and 1980.

The expected drawdowns in the coastal zone will provoke sea-water intrusion if no special measures are taken. Therefore recharge has been proposed of partially treated municipal and industrial waste waters and sewage in the littoral zone, to prevent salt-water intrusion taking advantage of the filtering and bacteriologically purifying capacity of sand and other fine-grained material which comprises the littoral zone (Comité Maghrebin, 1973; DEMRH, 1973f, g).

Recharge of Kharga basin through Toshka West. The eventual emergency spillway through Toshka West may allow transfer of excess surface waters over a distance of 200–250 km to recharge the Kharga basin, where groundwater decline has already taken place to a great extent (see pages 52 and 53). Lake Nasser will provide suitable water for recharge since the Nile silt has been left behind in Lake Nubia. As conveyance by open canal may allow desert dust to be

blown in, with the unfavourable consequence of clogging in the selected locality of recharge, it may be worthwhile to consider the construction of a pipeline. A pipeline enables the intake to be localized at a selected place and depth (level) in the Toshka West Khor, in order to obtain the clearest water. Moreover, a pipeline could transfer water from even lower levels than 183 m, for instance between 175 and 183 m, if it were pumped. Because of the artesian character of the Kharga aquifers, the recharge would have to be applied with sufficient hydrostatic pressure to overcome the artesian pressure. The transport of the recharge water by pipeline from Toshka West would then be obligatory. In this way, a part of the potential pressure of the pipeline water, which crosses the emergency spillway at 183 m above sea-level would be conserved to enable injection in the artesian aquifer.

Depending on the frequency and the length (in days) with which high lake levels are expected to occur in the future and the maximum amount of groundwater to be withdrawn from economic depths in the Kharga depression, the discharge capacity of the conveyance system can be calculated in order to sustain irrigation for at least the expected lifetime of the chosen conveyance system. Further studies are required in order to evaluate alternative cost estimates with and without water treatment, also with and without pumping, in order to lengthen the period of water transfer from Toshka to Kharga. At the same time estimates should be made of what part of the Nile discharge would be required in the Nile Valley itself and what would be the absolute minimum amount of water needed in Kharga in order to reach the solution which would best fit the development programme to be adopted by the Egyptian Government in the Kharga area (Gischler, 1974a; Kamal *et al.*, 1974b).

THE NEED FOR CONCERTED ACTION FOR INTEGRATED DECISION MAKING

The development programme to be adopted by the Egyptian Government has to take into consideration the salt balance of Lake Nasser–Nubia and the Nile. The interrelationship can be outlined as follows:

For an initial chemical composition of the Nile waters of 200 ppm the evaporation from a sheet of water with surface area of 1 km^2 and thickness equal to the yearly evaporation rate (for Aswan 2.20 m) will add

$$200 \times 10^{-6} \times 2.20 \times 10^{6} m^2 = 44 \text{ tonnes of salt}$$

to the remaining water volume. At this rate for a water surface of Lake Nasser–Nubia of between 5000 km^2 (lake level 171 m above the sea-level) and 6500 km^2 (lake level 183 m above sea-level spillway level) and a dissolved salt concentration varying from 220 to 250 ppm, there would be an annual increase of salt of between 2 million and 4 million tonnes.

If Lake Nasser–Nubia were a closed lake there would be a progressive and ultimately catastrophic salt accumulation. However, since water is continuously released at Aswan the salt concentration will increase in the lake until the quantity of the dissolved solids flowing into the lake is equal to the quantity vented by the lake or:

$$\sum_{t=1}^{n} Q_{\text{in}_t} \cdot C_{\text{in}_t} = \sum_{t=1}^{n} Q_{\text{out}_t} \cdot C_{\text{out}_t}$$

Q = discharge, C = concentration.

In addition to the original concentration, this extra quantity of salt is evenly distributed over the remaining huge volume of lake waters, and as volume (V) times concentration (C) will be constant (K), ($V \times C = K$); a decrease in volume due to evaporation will increase the concentration proportionally. Calculation has shown concentration to be less than 250 ppm. (Note – infiltration into the lake banks is neglected for simplification.)

Since the Nile discharge into the Mediterranean has been decreased on purpose to roughly $15 \times 10^9 m^3$/annum, mainly in the form of drainage water, it should be checked if the quantity of salt introduced at the upstream side of the cultivated Egyptian Nile Valley, is also released at the downstream side. If not, salt accumulation is building up somewhere in the cultivated lands.

The disturbing effect of more saline-leaching waters produced by drainage from virgin soils recently brought under irrigation, should be taken into account. Fortunately these additional quantities are well known, as the areas

where such phenomena have been observed have been studied in detail (Nubariyah). Also salt inputs originating from seawater intrusion along the coastal zone of the Nile Delta should be isolated from the problem under consideration, namely the salt balance of the Nile.*

Given the moderate variations in salt concentration of the river water which is at a maximum in July–August, and variations in salt concentrations of the drainage waters over a much wider range with a maximum in January–February, salt inputs and outputs in the overall balance should be computed over at least the period of one year. In order to analyse the problem in more detail the Nile plus its associated irrigated valley can be split into well-defined sections. In each section the specific allowable increase in salinity can be deduced on the basis of the consumptive water use of the crops and vegetation in that portion. This figure can be compared with the salt increase found by observation.

Knowing only water inputs and outputs with their respective total dissolved solids content and the areal extent over which they are applied, specific values of salinity increase per unit of area can be computed and extrapolated over larger areas as a basis for identifying areas with excessive accumulations of toxic salts with a view to taking corrective measures and deciding the regional priorities for such soil management.

Moreover, since the policy has been adopted to reuse drainage water with acceptable quality, or even to blend lower quality drainage waters with good quality river water, the salt balance will be indispensable information for water management control. The management procedures should include measures to reduce the excessive average water application now in use, 14 000–16 000 m^3/acre to about 8000 m^3/acre (or expressed in terms of cumulative height of applied water from 3.5 to 4 m/annum to about 2 m/annum). In this way, water will become available for the expansion of the irrigated area.

What has the management of Lake Nasser–Nubia to do with this problem. For reasons of water economy as well as water quality it is recommended that relatively low lake levels be maintained. However, this would exclude the recharge of Kharga and Dakhla regions. On the other hand high floods from upstream can be collected at any time without risk and without a flood forecasting system. It must also be remembered that the lake level affects the performance of the generating system which should operate optimally. From the point of view of water supply security, once the Toshka emergency spillway is operational it is recommended that relatively high lake levels be maintained. This will increase the possibility of having water available for recharge in Kharga and Dakhla and ensure adequate power generation. Flushing could be practised in order to combat excessive salt pollution if required. In the lower part of the Nile

*The Egypto-American project of 'The Quality of Lake Nasser and the Nile is making a constructive contribution to the solution of this problem by their painstaking composition of a data bank based on scruplous observations covering practically the complete gamut of water quality variables.

downstream of the Delta Barrage, the river is almost stagnant. This is serious in the Damietta Branch north of Mansoura, where the river channel is obstructed by submerged and floating aquatic weeds which resulted in the almost total disappearance of fish.

In order to optimize the potential of the High Dam, the lake levels should be maintained at the most suitable level. This level will depend on the probability with which dry and wet seasons can be predicted. High levels should be maintained when dry years are expected and low levels when wet years are expected. As the Nile floods depend on derivations to be expected from the average rainfall produced by the monsoonal air circulation, the study of the probability of rainfall linked with flood forecasting should receive the highest priority at advanced centres of environmental studies and in the relevant departments of national and international agencies such as the United Nations. The subject has very wide implications, much wider than for the management of the High Dam alone. Millions of peoples and many governments could take preventive measures to protect themselves against the excessive yearly variations in rainfall, and desert encroachment control projects could start at moments when they have a high chance of success in relatively wet periods.

An element of speculation will always exist. However, the promotion of intelligent speculation needs international and scientific encouragement as too many funds are demanded for the amelioration of deteriorating socioeconomic conditions in exactly that part of the world affected by high drought probability. Unfortunately countries in the area concerned cannot afford the failure of their development projects (National Research Centre, 1976; WMO, 1971).

GROUNDWATERS IN SECONDARY PERMEABLE MATERIAL

Geological setting

Beyond the boundaries of the stable shelf surrounding the Arbo-Nubian shield, the unstable shelf gradually changes into the geosynclinal Tethys belt, separating the Afro-Arabian basement complex from Europe and central Iran.

In the geosynclinal belt, under marine conditions, carbonate rocks, for example gypsum, have been deposited. After intensive folding they have been lifted up and form now the massive Jurassic, Cretaceous and Eocene formations exposed in the mountainous areas of the Middle East. These areas are the Lebanon, Antilebanon, and their continuations on both sides of the Rift Valley (Ghab, Bekaa, Jordan Valley, Dead Sea) and across the foredeep of the Mesopotamian and the Arabian Gulf, the Taurus and Zagros mountains, continuing in the Jabal Akhdar of Oman, south eastern Arabia. Also there are the more isolated anticlinal mountains linked with the different uplifts and down-warping of the faulted Basement Complex, reaching in Syria depths varying from 3000 m in north Syria to 8500 m in the Dawa basin. The Palmyrian mountains, Jabal Sinjar, Jabal Abd el Aziz and Tual el Aala, receive less precipitation than the former higher mountains. The Jabal Akhdar, east of Benghazi in north-east Libya, although outside the region concerned, should be considered to belong to the latter category.

On the Arabian Gulf Coast these limestones, dolomites, gypsum and rock salt layers are less folded and are covered by Neogene and Quaternary marine and lacustrine deposits containing sebkhas, in a zone extending 100 km from the present coastline.

Hydrology

The total thickness of these Secondary sediments normally exceeds 2000 m. They generally lack any intergranular porosity and depend on secondary openings imposed by tectonics (folding, faulting, jointing) often widened afterwards by solution, to store and transmit groundwater. This process of solution takes place where groundwater containing aggressive carbon-dioxide can penetrate and circulate, and is called karst formation. Karst formation may have taken place in the past (palaeokarst) or be current. The former type of karst may have been removed by erosion or may have been blocked later with alluvial infill material.

Aquifers in such formations with secondary permeability, consist of widely coherent, confined groundwater bodies of regional extent, locally separated from each other by layers with higher clay content forming marly aquicludes.

These aquifers discharge into:

(a) A series of scattered perennial karstic springs in the periphery; this zone may be wide and sometimes remote from the above-mentioned mountainous recharge area. If the area is intersected by a coastline, discharge may be in the sea as a sub-marine slip.
(b) Semi-unconfined overlying Neogene or Quaternary aquifers, where the groundwater increases rapidly in salt content due to evaporation (sebkhas) or the presence of clay layers containing much salt.

The hydraulic systems supplying the springs

The most famous of karstic springs are given in Table 9. Comparing these yields for instance, with the large-scale groundwater withdrawal from the Nubian aquifer in Kufrah (about 4 m^3/sec obtained with the help of 61 pumped wells) may give an idea of the high underground transmitting capacity. It allows groundwater from a wide surrounding area (certainly in the case of Hofhuf) to obtain access to such a spring. This means that the massive karstic groundwater circulations drain large limestone areas, consequently reducing surface flow. The springs represent an ideal water supply source, since such sources can be readily developed. If these waters have the right chemical quality they need only piping

Table 9. Some characteristics of important karstic springs in the area

Name of spring	Yield	Region	Recharge area
Ras el Ain	40 m^3/sec	Syrian–Turkish border	Taurus
Ain el Aarous	6 m^3/sec	Syrian–Turkish border	Taurus
Ain Barada	7 m^3/sec	West Syria	Anitlebanon
Ain Figeh	3–20 m^3/sec	West Syria	Antilebanon
Ain Zarqa	Most important spring feeding the Orontes	Bekaa	Lebanon
Ain Sheqqa	Sub-marine spring	20 km SW of Tripoli	Lebanon
Fresh water wells on the isle of Arvad	?	45 minutes by boat from Tartus Syria	Middle Eastern continent
Ain' Zayanah	Sub-marine spring	Coeffia east of Benghazi (Libya)	Jabal Akhdar, north-east Libya
Hofuf Oasis	14 m^3/sec	Gulf Coast	?
Springs of	Sub-marine spring	Arabian Gulf	?

and bacteriological examination, to ensure sufficient purifying and filtering takes place in order to supply the population centres.

The next step is to exploit springs at a rate satisfying the actual demand through the year. This rate normally does not correspond with the natural fluctuations of the spring yield. In the case of the Figeh spring providing Damascus with excellent municipal waters, the World Bank is providing substantial financial aid to allow the spring to be more intensively exploited in the future. Over-exploitation of the spring during periods of low discharge, drawing water from storage, is based on the assumption that the storage will be restored in periods of high discharge which exceed the needs of the urban population.

Unfortunately the development of springs by regulating their yield is a risky undertaking, and is only justified when the following parameters are known, which normally is not the case.

(a) The delineation of the system supplying the spring.
(b) The amount of recharge.
(c) The storage capacity of the system.
(d) The period of time the water is in the system (residence time).
(e) Eventual interdependence of different springs supplied by the same system.

The use of isotope techniques for hydrology

Conventional hydrological observational techniques to determine the water balance of a limestone basin by means of computed factors like precipitation, river flow and evaporation losses may sometimes lead to confusing results, especially since the surface water divides will not necessarily correspond with the groundwater divides. In this connection the, as yet, unconventional environmental isotope techniques whose merits have been recognized in principle, provide an adequate alternative method. They make use of the isotope oxygen-18, deuterium and tritium, naturally present in various concentrations in waters of different types. Isotope methods allow not only the 'fingerprinting' of these waters, but also, if combined with quantitative hydrological measurements, they allow the computation of the proportion in which each of these differentiated waters contribute to the total yield of a borehole, spring or river, at the moment of observation.

The moment has arrived to integrate isotope surveys as an essential method in the water balance studies of limestone areas compensating for the non-applicability of the conventional hydrological observation. For this reason the hydrological surveys of countries such as Iraq, Jordan, Syria and Lebanon have keen interest in the establishment of an environmental isotope laboratory. It was at the request of those countries that the Arab Centre for Studies of Arid Zones and Dry Lands (ACSAD) asked the assistance of UNESCO to conceive a preliminary study using environmental isotopes for the identification of surface/groundwater systems in order to determine their quantitative functioning in

Arab countries of the Middle East. The study would be executed jointly by the International Atomic Energy Authority (IAEA) and UNESCO.

The basic ideas were:

(a) To find out to what extent isotope investigations integrated with other surveys like geophysics, tectonics, underwater exploration and snow surveys (so far neglected in the Middle Eastern mountainous regions) could contribute to determine the previously mentioned unknown parameters of the hydraulic systems feeding the springs.
(b) To establish a regional isotope laboratory for hydrology.
(c) To link the isotope laboratory with a regional hydrological research programme exploiting to the full the possibilities of the isotope techniques for Middle Eastern limestone hydrology. Such a programme would also guarantee the exploitation of the full laboratory capacity in an adequate manner, this being a major difficulty with newly introduced technological establishments which could easily reduce their economic returns.

It should be realized that so far scrupulous research has been carried out in the Western countries in the development of isotope techniques for hydrology. Consequently examples were studied under the moderate climatological conditions ruling in the areas surrounding these scientific isotope centres. In contrast the semi-arid environment of the Middle East with accurately localized recharge and discharge areas, nicely separated in space and with well-defined periods of precipitation, offers much better possibilities for distinguishing the different types of water. In their turn these conditions are very favourable for the use of environmental isotopes for hydrology.

After the ACSAD request was submitted to UNESCO headquarters for comment, it was decided to discuss the proposed collaboration between IAEA and UNESCO in Vienna. The final result was a modification of the basic idea into the following two projects:

(a) 'The establishment of a regional centre for hydrological studies by radio isotopes in Jordan.' This project was presented by the Government of IAEA as the executing agency.
(b) 'Water balance of the Western Limestone complex of the Middle East (first phase).' This project was presented by ACSAD on behalf of Jordan, Syria and Lebanon to be executed by UNESCO. UNDP has given priority to the project which, however, due to the political strife in Lebanon, may be delayed for some time.

Sub-marine fresh-water springs

The proposed UNDP/UNESCO project is restricted to the limestone massifs alongside the Rift Valley (Ghab–Bekaa–Dead Sea), while also considerable attention will be given to the unknown part of the groundwater which disappears along the Mediterranean coast in the form of sub-marine springs on the coastal platform.

An airborne infrared imagery survey was made along the Lebanese coast by order of the UNDP/FAP hydro-agricultural project of South Lebanon. Infrared imagery records the infrared electromagnetic radiation emitted by the detected body, being a function of its absolute temperature (in degrees Kelvin). As such it reflects the temperature of the body or material to be examined, in this case the sea surface along the Lebanese coast. The survey resulted in the accurate location of a large number of offshore springs. A preliminary estimation made of the fresh-water losses along the Lebanese coast gave figures between 70 million and 400 million m^3/annum, or between 2 and 13 m^3/sec. This estimate was made as follows:

> The temperature deviations characteristic of the presence of a sub-marine spring have been interpreted quantitatively by comparing them with the temperature deviations caused by a debouching river with a known water temperature and known yield.

The survey was made in the late spring, when the rivers discharge snow-melt water from the mountains into an already warming sea. It was assumed that all sub-marine springs supplied water of the same low temperature as that of the river.

> The product of the surface area of the cooled-off water with respect to the average sea surface temperature, and the actual temperature difference, for every part of the area of influence, gives the amount of fresh water leaked from the sea bottom, using the temperature deviation produced by the known river discharge as a conversion factor (Chapond, 1973b).

This approach was reasonable since no additional data were available but its result should be considered provisional until further observations are made at sea to assess the performance of the sub-surface fresh-water sources (Kohout, 1966).

The underwater investigation of the Société des Eaux de Marseille

The sea-level in the Mediterranean must have been 100 m below the present level during the last Würm Glacial maximum. The occurrence of the karst at the same level has been found in the south of France, where it is assumed that this former base level of erosion is related to this deep level of karst formation. When afterwards the sea submerged these karst systems, the limestone galleries were subjected to a different weathering regime as sea water is not active in dissolving limestone whereas fresh water is extremely active. Subsequent to inundation by sea water, karst formation has been restricted to the roof zone of the uppermost pressure galleries. With the inland movement of sea water and its inactive chemical behaviour, the deeper galleries tend to have silted up or to be blocked in one way or another.

A number of boreholes were drilled in the Lebanese coastal zone to determine whether the same phenomena could be detected there. The boreholes

produced brackish water after having first yielded fresh water, proving the penetration of the sea-water wedge inland at the bottom of the karst galleries.

Near Marseilles the Société des Eaux de Marseille explored such a karst system through which the sub-marine spring of Port Miou is fed. They found that the dynamic role of the sea water reacted mainly inversely with the pressure head variations of the fresh water, neglecting the secondary effects of tides and wind. Specially designed equipment to measure a series of parameters over periods of considerable time, by making a recording every ten minutes, was placed in the karst galleries and exchanged every three months by underwater explorers. The recorded parameters were: current velocity, direction of current, electrical resistivity, temperature and pressure. From these data it proved possible to reconstruct the regime of the karst spring and on the basis of the results an underwater barrage was constructed to prevent the sea-water wedge from penetrating inland upstream of this construction. The fresh water was in this way allowed to build up its pressure, and water could be withdrawn upstream of the structure for water supply purposes without allowing sea water to mix with the fresh water. The estimated costs per cubic metre including the investments made for research were estimated at less than one centime (1/100 of a French franc) this being mainly because these karstic springs, noticed by man, supply very substantial yields (Potié *et al.*, 1973).

The same group of the Société des Eaux de Marseille also made underwater exploration of the Ain' Zayanah sub-marine spring. This spring is fed by fresh water from the Jabal Akhdar in north-east Libya which circulates on top of more saline water in the karstic collapsed structures of the Coeffia region, east of Benghazi. If it were possible to isolate the fresh water from the underlying saline water an elegant and cheap solution could be found for the urgent water problems of Benghazi, which have meanwhile been solved by sea water and groundwater desalination.

After a first underwater reconnaissance in May 1974, a large-scale investigation took place from July to October 1975; 4.8 km of submerged galleries were explored to a depth of 80 m below sea-level. One of the conclusions was that one main gallery discharged 4–5 m^3/sec to the Blue Lagoon, which is directly connected with the sea. The water contains 4–6 g of salt/l and is a mixture of two kinds of water; about half the discharge originates from freshwater circulations with 1 g of salt/l while the other half of brackish water comes from deeper levels by way of two karstic shafts, which contain 4–10 g of salt/l.

Since the Mediterranean sea contains about 40 g/l, there are two possibilities: either the water, which originates from deeper levels has its own characteristic salinity of 9–10 g/l, or this concentration is a result of mixing. The latter explanation is more probable since the sea is near. By modifying the hydrostatic equilibrium the fresh-water component might be separated from the salt-water component of the water originating from deeper levels (law of Ghyben-Herzberg). This could be effected by closing the main discharging gallery and increasing the hydrostatic pressure at the inland side with respect to sea-level.

In order to prevent possible unforeseen irregularities more investigation has to

be carried out before an entire karst system can be put under pressure by blocking the main gallery. If this karst system in northern Libya would support the increase of pressure and the deeper waters could be differentiated, more than half of the present discharge being 4–5 m^3/sec might be obtained for water supply purposes in the Benghazi area.

Water balance of the Western Limestone Complex of the Middle East

It is the intention of the proposed UNESCO project 'Water Balance of the Western Limestone Complex of the Middle East' (first phase):

(a) To fix the boundaries of some representative recharge – groundwater – discharge systems.
(b) To establish the water balance of such a system by solving the required parameters in order to understand the quantitative functioning of the system in time and space. The parameters include the amount of recharge, storage and residence time.
(c) To study the alternative possibilities of capturing the waters of the most suitable of these systems.
(d) To make a cost estimation for the development of these fresh-water resources, hitherto wasted.

In an integrated way a use will be made of the following disciplines

Tectonics to trace the fault zones in which continuation of the springs can be traced.
Snow surveys to estimate more accurately the recharge.
Geophysics to trace the inland penetration of the salt-water wedges on the bottom of the karstic systems.
Isotope techniques in order to find the origin of the spring water in mountainous regions and to determine the residence time of water in the karst systems.
Underwater exploration methods to reconstruct the accurate regime of springs.

The Neogene Fars formation (see Table 9)

The Neogene Upper Fars and even more, the Lower Fars formations in the Syrian Jezirah and north-western Iraq, are notorious for their low permeability due to high clay content, and for their high salinity groundwaters. This forms the major problem of the development of this area. The water supply problem can be partially solved either by bringing in water by pipeline from the bordering region or by desalination of inferior groundwaters.

Umm er Radhuma limestone aquifer

The aquifer with the highest transmissibility in the Arabian Gulf area is the Paleocene Umm er Radhuma formation with a thickness of 300–500 m. This

formation covers the Maestrichtian Aruma formation in which occur the Khobar aquifer (Alveoline limestone) of 5 m and the Alat limestone aquifer of 10 m. In spite of their restricted thickness both aquifers are of major regional importance. These formations are overlain by Neogene marine deposits which grade inland into terrestrial deposits.

The three aquifers show both primary and secondary openings. They show karstic features which are most developed on the crests of domes and anticlines in the fold areas. Here the aquifers behave as a simple groundwater hydraulic system, with interflow of groundwater and pressure equalization. However, in places, intercalated aquicludes cause marked differences in salinity, pressure and yield. Taken on a regional scale, the three high transmissibility aquifers should be considered as one. They occur from the Iraqi borders in the north, to the Rub al Khali, throughout Kuwait and the eastern province of Saudi Arabia. They extend also under Bahrain Island and large parts of the Arabian Gulf. But the fresh-water aquifer system is cut off from Qatar because of a steep anticlinal Dokham dome on the western edge of the Qatar peninsula. On the east side the Umm er Radhuma aquifer contains saline water. The highest transmissibility is encountered in the Arabian Peninsula. On a regional scale it is ten times larger than the transmissibility observed in individual pump tests. This is typical for the aniosotropic karstified nature of these limestone aquifers (Durbaum *et al.*, 1972).

The storage capacity is not well known as this is much more difficult to determine than the transmissibility.

The natural discharge from the aquifer system as a whole takes place through terrestrial springs, sub-marine springs and evaporation from sebkhas formed in more recent times. The most important terrestrial springs are those feeding the Hofhuf oases (14 m^3/sec). Sub-marine springs are by definition less evident, however there are numerous accounts of such springs in the Gulf. Some have been located and mapped with care, but the total number of such sub-marine springs and their combined discharge of fresh and brackish water is unknown.

Seepage upwards through the overlying Neogene and Quaternary is considered to be a major discharge mechanism. The water is finally evaporated from the sebkhas, which occur along the coast. Their total annual evaporation losses in the coastal region of Saudi Arabia have been estimated to amount to 500 million m^3/annum or 16 m^3/sec.

In many areas the Umm er Radhuma outcrops are marked by overlapping Miocene–Pliocene deposits: southward from Wadi al Batin, Radhuma is in part covered by aeolian sands of the Dhana desert where occasionally infiltration may occur. In the west the Umm er Radhuma outcrops over more than 1000 km parallel to the general north-west–south-east strike direction of the sediment stratification. Much of the groundwater stored in, and moving through, the aquifer system originated from past pluvial periods. Present day recharge is small and is less than the current natural and artificial discharge, and there is evidence to show that over the past 50 years depletion has occurred at a steady rate; and that this depletion was taking place before groundwater development and extrac-

tion by boreholes had even commenced. It is thought that when the wadis, now dry, were flowing, the aquifer might have been full up to the level of the thalweg of the valleys. Steady declines in groundwater levels caused the streams to dry up.

There also appears to be sub-surface transfer of groundwater from the deeper, more highly pressurized and warmer waters of the underlying aquifers, mainly in anticlinal dome areas.

High rates of extraction of groundwater from flowing and pumped wells has led to sea-water encroachment along the coast. In some places the development has been careless and high-pressure aquifers have been allowed to leak into lower pressure aquifers through badly constructed or uncased boreholes, while the lack of regulation of the flow has led to a waste of water. To a great extent these wasteful groundwater extractions have been cured by cementing and casing the existing inadequate wells and replacing them by more efficient structures. The total dissolved solids content varies from 1200 ppm, and even less near the outcrops, to 55 000 ppm.

The hydraulic gradient varies from the water-table conditions to artesian conditions, as in Wadi Mirah where a deep well produced 126 l/sec with a pressure head of 7 atmospheres. Although much quantitative data exists on the Umm er Radhuma aquifer, as far as is known to the author this has not be synthesized into a comprehensive water balance of the aquifer system (Burdon, 1972). It is quite clear that the aquifer has still untapped development potential, and a regional water balance study including Kuwait, Bahrain, eastern Saudi Arabia and eventually the coastal zone of Iran, is urgently required.

Mohammed al Kharagi's theory (AD 1017)

The importance of fresh-water losses into the Arabian Gulf may be illustrated by the following remarks made by the Iranian scientist and (hydronomist) Al Kharaji in AD 1017, who lived west of Isfahan in the Zagros mountains.

The following quotation comes from his book, *Kitaab Inbat al-Miyah al Khafiyya:*

> 'Of these mountains the slopes which face north are more humid than those facing east or west without mentioning the opposite slope on the south, being the spot, from where the sun, heating from the morning till the evening during the entire year, removes the most fresh and subtle parts, which it metamorphoses into air.
>
> 'It is for the same reason that the sea water at the same time is bitter and viscous (thick), as the sun has robbed it in the course of the ages of its most fresh and subtle contents.
>
> 'This metamorphosis is detrimental to the surface layers of the sea water, while the sea water on the bottom has stayed fresh.
>
> 'The proof is that the sailors draw their drinking water from the bottom of the sea.

'In order to do so the sailors use a leaden container with a regularly perforated bottom. The bottle-neck of the container in question is fixed to a long tube made of dressed skins and rubbed with wax to make it waterproof. The bottle-neck of the container is plugged. The plug is attached to a thread as long as the tube.

'One lets the container sink until it touches the bottom. One pulls the thread fixed to the plug. Immediately air escapes from the container and the fresh water from the sea bottom flows in through the tiny holes in the bottom until it is filled up. At that moment one lifts the container by a rope previously attached to the handle'.

From this it appears that Al Kharagi was misled by the exceptional situation which exists in the Gulf, which made his theory in a way plausible. As Al Kharagi must have obtained this information from the sailors of the Gulf, it is also probable that along that coast fresh water discharged into the sea. In that case the recharge area is evidently the high Zagros range reaching over 4000 m in altitude. Here probably each year a considerable amount of precipitation may be collected which may find its way underground to the Gulf. Indeed there exist rivers that disappear in karstic formations, while their re-emergence so far in the form of springs at lower levels, has not yet been found. For this reason it would be appropriate to include the Iranian coastal zone as far as the Zagros water divide in any water balance study of the area surrounding the Arabian Gulf, and it should be co-ordinated with an oceanographic programme in this area.

TECHNOLOGICAL MODIFICATIONS OF THE HYDROLOGICAL CYCLE

Utilization of saline waters

After natural fresh waters have been used for human and animal consumption, for irrigation and industry, the part which is not evaporated will be enriched in total dissolved solids and will normally be drained farther downstream with the sea as an ultimate drainage terminal. In arid regions it may happen, with or without human interference, that all waters, before they have reached the sea, have become so saline that without further treatment they are unsuitable for human consumption and even for irrigation and industry.

The UNDP/UNESCO project Tunisia 5, 'Research and Training on Irrigation with Saline Waters', executed in the period from 1962 to 1969, aimed at formulating, under the cultural conditions of Tunisia and on an agricultural scale, the standards for the utilization of saline water for irrigation (UNESCO, 1970).

The important parameters of salinization and alkalinization are the following:

1. The type of soil, with respect to its capacity for salt fixation.
2. The presence or absence of a shallow water table which, if fed by an excess of irrigation water, may rise progressively and reach the root zone of the crops.
3. The amount and distribution of annual rainfall; factors which affect leaching.
4. The several factors influencing the evapotranspiration such as temperature and wind velocity.

Soil salinity can be controlled by leaching. Leaching can be induced through percolation, therefore it is necessary that the soil moisture content reach field capacity and that an amount in excess be supplied. In the case of frequent leaching the salinity of the soil solution tends towards that of the irrigation water. Based on this principle, tests have proved that even by applying water with 2–4 g/l of dissolved solids content, salinity can be held effectively under control with an intensive to slightly excessive irrigation regime.

The higher the vertical permeability of the soil, the more saline water can be used for irrigation, on the condition that the water applications be carried out with the strictest discipline in order to avoid harmful results.

Since crops differ from one another with respect to salt tolerance, the sensitivity of the crops has to be determined as well as the methods of growing them in an economical way without sterilizing the soil.

Atmospheric water diversion and weather modification

Tapping the rivers of the sky by cloud seeding

If the salt content becomes so high that even these simple leaching methods are no longer applicable, the only way to obtain good quality water is to remove the salt partially or completely from the water. The separation of the water from the salt requires the addition of energy. In nature this is realized by the addition of solar energy into the entire space occupied by the earth's atmosphere. The earth's surface is the inner boundary of this space and also the source area from which water can be evaporated and to which the condensed waters can again be returned purified from the salt content. The only problem is that precipitation does not always take place where one would like to have it.

There is reason to believe that this can partly be solved by weather modification procedures. In the middle seventies, United States scientists found that the headwater region of the Jordan river offered a topographic situation favourable for the formation of clouds through cloud seeding. During the winter months potentially unstable air frequently flows across the region. Temperatures aloft in the moist air are characteristically cool enough to justify seeding.

The scientific research programmes in the USA to 'tap the rivers of the sky' at that moment contemplated expenditures in excess of $US 500 000 a year over a 10–20 year period. By now the results of the research are sufficient to carry out full-scale field applications on a river basin like the Colorado in the west of the USA, an area which is in many ways comparable with the Jordan river drainage area. It was believed (in 1967) that successful seeding in the Jordan River headwaters region could be expected to generate 100 000 acre/ft = 123 350 000 m^3 or 10–20 per cent of the annual runoff, this being a conservative figure at the very modest cost of $US 0.4/1000 m^3.

It has now been established that increasing artificial rainfall in a certain region will decrease the chance of precipitation in the leeside direction of the region in question. So only in cases of isles receiving little or no rainfall, where the sea extends in the downwind direction, allowing recharge of the depleted moisture content of the atmosphere, may cloud seeding be applied without harmful side-effects.

Diverting another country's cloud system could be construed as an illegal diversion of its water. From this point of view, it would be more acceptable to reduce rainfall where there is a recognized excess of rainfall (in a certain season) if such areas could be identified. In adjacent regions of surplus and deficient precipitation originating from the same regular air circulation system (monsoon) a rainfall reduction of for instance 5 per cent in a region with excess rain could result in an increase of 25 per cent in a semi-arid region in a down-wind direction, this would be to mutual interest for the countries in the area concerned. The entire transitional belt from the rainforest to the savanna at both sides of the equator might be considered as a region which could benefit from such shifts of rainfall.

Such an imaginative atmospheric water diversion experiment could be com-

pared with the ongoing disputed surface water diversion carried out in the Jonglei area of southern Sudan (Gischler, 1975a). Another large region with areas of excess and deficient rainfall from one well-defined atmospheric source, and one from which experience may be gained, is the Indian subcontinent (Gischler, 1976, 1977). After examining the desirability of such atmospheric interference it may be worthwhile to consider the orientation of research in this direction.

Intentional and unintentional weather modification

The development of weather modification technology has gone through a paradoxical experience in its short existence. On one hand the more scientists learn about the weather, the more they realize that it is a subject of enormous complexity with a myriad of built-in feedback systems about which the quantitative functioning is practically unknown. Therefore they may propagate a non-interference policy in weather processes. On the other hand scientists have come to recognize that unintentionally man has become involved in a world-wide uncontrolled weather modification experiment through the return to the atmosphere and oceans in the short space of two centuries the total amount of exploitable concentrated organic carbon stored in the earth's sedimentary rocks over a period of hundreds of millions of years. This process started about 100 years ago when during the first industrial revolution a beginning was made with the combustion of coal and later petroleum,* natural gas and oil shale, to meet the continuously increasing energy demand. Carbon was liberated from the fossil fuels and has been released at an exponential rate in the form of CO_2 to the atmosphere. CO_2 is transparent for incoming solar radiation but absorbs the infrared radiation returned by the earth towards space. On these grounds it is supposed that an increase of CO_2 content would warm up the atmosphere by the so-called 'greenhouse' effect.

So far, about 50 per cent has been absorbed again mainly by the joint surface area of the oceans with its restricted absorption capacity for CO_2, controlled by the H_2CO_2–HCO_3 natural buffer system, and has subsequently been transmitted to the deeper regions of the oceans. However, it is doubtful if the ocean surface will be able to absorb CO_2 at the exponentially increasing rates of production. Instead of partly compensating for this increase of CO_2 by induced photosynthesis on a large scale through for example afforestation, on the contrary the scale of land destruction in the last 20 years or so has reached unprecedented proportions. According to the latest estimates, in the low latitude zones of the world, a semi-arid area equal to the size of Brazil has been degraded through

*The latest estimation (August 1977) of the total world petroleum reserves is 300×10^9 tonnes, including the off-shore reserves in waters up to 200 m deep and those in Arctic regions. 42 per cent of these reserves are located in the Middle East and North Africa. Certainly no more than at most 50 per cent of this quantity will be exploitable. At present the degree of exploitation is 25 per cent. In 1977, world petroleum consumption amounted to 3×10^9 tonnes.

desertification, overgrazing, burning and injudicious farming, and therefore aggravating the effect of the carbon liberation to the atmosphere. Land degradation and burning further created dust bowls which supplied probably 30–50 per cent of the very small solid particles present in the air, known as aerosols. Aerosols also intercept incoming solar radiation and outgoing infrared radiation. Opinions differ about the overall effect of the increase of aerosols.

The natural pattern of weather and precipitation fluctuations which otherwise might have been unravelled today by careful monitoring, has now possibly been overshadowed by man-made weather interference. On the basis of oxygen-18 analysis of land ice cores in Greenland, climatic fluctuations have been reconstructed accurately over a period of the last 1400 years. By extrapolation of the fluctuating trends a change towards cooler temperatures was predicted for the coming century. This trend has now probably been cancelled out by the CO_2 increase. The CO_2 increase may also have an important impact on rainfall and rainfall distribution in space and time as is indicated already by the extreme climatic events which have succeeded each other with an unprecedented speed in the past two decades. Those who suggest that man is trapped in an uncontrolled and unintentionally man-made weather modification experiment have some evidence to support their contention.

Tapping the rivers of the sky by vegetation

Another more harmless way of harvesting the moisture content of clouds or haze banks is by planting appropriate trees on the slopes at altitudes where these banks are formed. Some trees, pine trees especially, and plants in general have the property of collecting water from moist air as a function of their surface area.

Although this was observed and measured carefully by the author along the Pacific coast of South America, no well-documented example of this phenomenon in the Arab world is so far known to him. However, the grazing resources of the Darfur uplands of western Muscat and Oman are wholly dependent on the utilization of atmospheric condensation. There is no precipitation but the high humidity levels associated with the on-shore air movements of the summer monsoon bring sufficient moisture to sustain an important grazing resource.

Desalination

Solar distillation units

Condensation of moisture mostly occurs far away from the place where it originated by evaporation, while water shortage may occur at the site of the evaporation. To solve this problem an experiment has taken place in Sudan with great success, making use of simple solar distillation units. These could satisfy the water needs of areas with small populations and relatively non-industrialized

societies. The experimental solar still installed on the roof of the Solar Energy Institute, Faculty of Engineering, University of Khartoum, provides 1 gal of water/day/m^2, while installation costs of a 1 m^2 glass covered still amounted to five Sudanese pounds. For an assumed amortization of ten years the cost of distilled water is LS 0.001 gal. Plans for the construction of two 1000 m^2 pilot plants, one in Khartoum province and one in Kordofan province, are underway (Hamid, 1975).

All thinly peopled coastal areas in the Middle East and some inland areas are in principle suitable for this rather simple technology which does not require any extra energy input, except the freely available solar radiation.

Controlled environment

Considering the potential sites for future solar distillation plants, it has become clear that in most larger coastal communities of the world some waste thermal energy is available. These wastes are either from municipal power centres or individual private power-generation facilities which are more economical than solar energy.

From both the sociological and economic points of view it would be desirable to produce at least part of the food consumption of a coastal community within that community. However, the conventional type of agriculture would be too expensive on the basis of desalted water. Controlled environment agriculture would supply the solution to this problem.

By reducing the space in which the hydrological cycle takes place in specially developed enclosures, in which sunlight can penetrate and humidity can be controlled, high agricultural productivity can be achieved. Apart from a little high quality irrigation water and fertilizer, carbon dioxide has to be added in order to enable the continuation of photosynthesis, for in a closed environment the plants quickly use up the available carbon dioxide. The high humidity suppresses transpiration and evaporation. In the winter, the humidity is so high that moisture condenses on the cool walls of the greenhouses. This condensed water is then collected and reused.

In the 2 ha controlled environment greenhouses at Abu Dhabi, annual yields of 370 tonnes of tomatoes have been obtained in this way, and 600–750 tonnes of cucumbers. It was also possible to grow three to eight lettuce crops per year.

A similar project is being executed in Puerto Pinasco, Sonora, Mexico. Here the desalination plant of 6000 gal/day or about 23 m^3/day, provides sufficient water to meet the requirements of a 20 000 ft^2 or 0.1858 ha experimental greenhouse area, and supplies the drinking water bottling facility operated by the University of Sonora for the residents of the city (Clawson *et al.*, 1970).

Types of desalination plants

If so much water has to be desalinated that it becomes too costly to collect the evenly spread solar energy required for it, other sources of energy, easier and

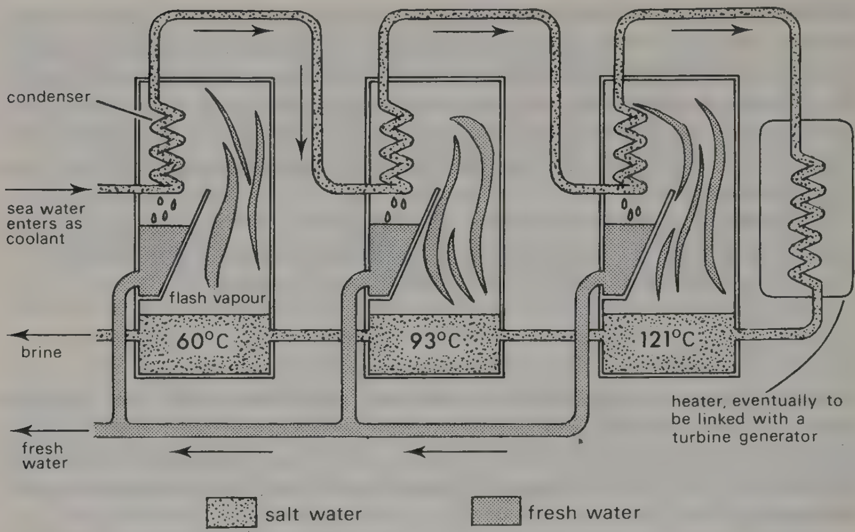

Fig. 11. A multi-stage flash distillation process.

Source: Modified from 'Chemical and Engineering News', 8 June 1970.

cheaper to concentrate, have to be considered. *Electro-analysis*, which is a membrane process, requires little electrical energy for brackish water conversion. In this category there is also the more modern development of *reverse osmosis*, or hyperfiltration. This is the reverse of osmosis, being the transfer of pure water across the membrane into a solution. When pressure exceeds the osmotic pressure, water will cross the membrane in the opposite direction and be purified. For this process strong membranes are required to stand the high pressures which are now generated. Trial plants have been constructed with capacities of 50 000 gal/day, or almost 190 m^3/day.

The output of these plants is water with 500 ppm or more. Better quality can only be obtained by increasing considerably the costs. At present the new city water supply for Riyadh in Saudi Arabia is based on such a system.

Besides freezing desalination units, the most common large scale desalination processes incorporating the principles of the natural hydrological cycle, are those based on distillation, namely multi-flash, submerged tube, long tube vertical and vapour compression (Fig. 11). The first two processes can conveniently be combined with power production while the latter can be combined with salt production. The output of these plants is water with maximum of 50 ppm similar to rain water.

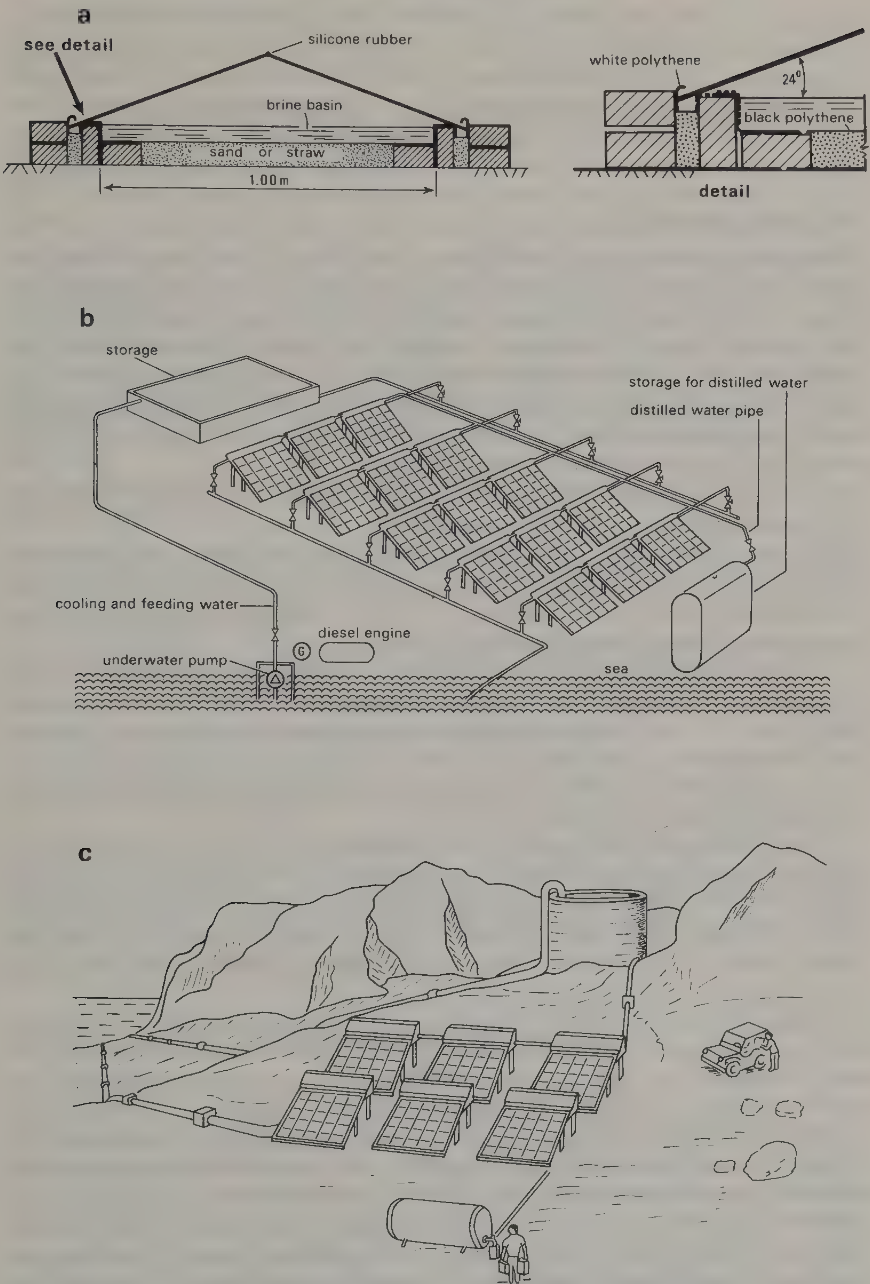

Fig. 12. Schematic illustration of water desalination plants.

INTEGRATED TECHNOLOGY AND ITS IMPACT IN ARID AREAS

The general principle

A technological development which has and will have a great impact in the arid coastal areas of the world in the coming decades is water desalination. At present the most productive agricultural areas in the United States are the desert areas where there is abundant sunlight. The Arab countries, occupying 18 000 km (56 per cent) of the total 32 000 km desert coastline of the world, could make these coastal zones very productive. Sunshine will allow the production of crops, in many cases, during 12 months of the year as long as soils are present and fresh water could be made available.

If no natural fresh water resources occur, desalination should be the answer if the presence of energy resources will allow it.

In 1969, 627 water desalination plants all over the world produced 225×10^6 gal/day or almost 10 m^3/sec. In 1975, the estimated world production of desalinated water was 10^9 gal/day or 44 m^3/sec. Of this amount 2.5 per cent was produced in the Arabian Peninsula alone.

The total installed capacity of Saudi Arabia will be almost 14 m^3/sec in 1985, as much as the total yield of the springs supplying the Hofhuf oasis. The investment made for this purpose is estimated to amount to \$US 7×10^9 (Saline Water Conversion Corporation, 1975). Where possible, these desalinated waters can be mixed with inferior groundwater, increasing considerably total potable water output by 30–50 per cent.

Today almost all large-scale thermal distillation plants are dual purpose plants for the production of both distilled water and electric power. The two functions can be coupled in an advantageous way. High temperature steam is applied for the production of electricity in a turbine generator, while the exhaust steam, as a low quality heat source, is used in a sea-water evaporator for the production of fresh water (see Fig. 11).

Although nuclear reactors provide today the cheapest method of very large-scale electrical power generation, locally more conventional methods may be more economic for electric power generation on a more moderate scale. In Saudi Arabia, for example, all plants are fossil fuelled since the country is wealthy in oil and gas. Along the Red Sea coast fuel oil from the Jeddah refinery is used, while in the east, waste flare gas from the Arabian Gulf area is utilized. Each of these areas, the Red Sea coast and the Arabian Gulf coast, contribute to about 50 per cent of the national production of desalinated water (Saline Water Conversion Corporation, 1975). The combustion product of oil and gas could also provide, after filtering, the carbon dioxide for introduction into greenhouses for the stimulation of crop production.

Although desalted water is still relatively expensive, much has been done to make it cheaper by enlarging the plants, based on the principle of economies of scale, and by the integration of water production with power production as has been mentioned before. To give an example, a plant with an output of 1 000 000 gal/day delivered in 1965 water for $US 1.25/1000 gal or $US 0.33/m^3. A modern purpose nuclear plant with an output of 100 times as much produced in 1974 water for $US 0.25/1000 gal or almost $US 0.07/m^3. Although the increase of prices has affected these figures, it is certain that in the fully integrated, nuclear-powered agro-industrial complexes, the rates of return for the massive investments required for such complexes can be increased considerably. These increased rates of return have been obtained by the ingenious integration of fresh-water production with power production, fertilizer production, crop production and with any other combination which may satisfy existing demands of the local economy. Meanwhile the oil-rich states using crude oil to energize desalination plants and power stations have been advantaged by the increase in oil prices.

The advantages of combining these technologies into a more integrated complex are the following:

1. The energy source can be larger than would otherwise be the case. Because of economies of scale, the unit cost of power, and therefore of each of the products, is reduced.
2. By-products or waste products from one process can serve as raw material for adjoining processes.
3. In such complexes specialized management can be shared to a great extent as well as operation and maintenance facilities.

The last point is certainly of great importance in developing countries.

It has been estimated that by developing only 5 per cent of the world's desert coasts, equivalent to 1500 km to a depth of 32 km, using such systems as shown in Fig. 12, food for one billion people could be produced (Fadalla el Tag, 1976). Of course the cultural background and the economic development level of the coastal areas have not been taken into account, which reduces the value of this, therefore, rather theoretical statement.

The Qatar example, characteristic for the Gulf Coast area

Hydrogeology

Under the Qatar peninsula the Palaeocene Umm er Radhuma formation contains saline groundwater on which the fresh-water lens floats which constitutes the natural fresh-water reserve of the country. This fresh-water lens is maintained almost exclusively by indirect recharge of the storm-water runoff of occasional rains during the winter, ranging from less than 5 mm to over 200 mm/annum, into about 850 approximately circular depressions which collect these waters and transmit them to deeper levels where percolation has increased the regional

permeability. These depressions are the surface expression of the solution of gypsum and anhydrite beds of the Lower Eocene Rus formation, which caused the collapse of the covering Dammam Middle Eocene limestones, being the formation which is most widely exposed at the surface in Qatar.

There is evidence that recharge varies from the north to the south of Qatar and that the existence of the northern fresh groundwater lens is the consequence of the absence of sand deposits in the depressions which are generally devoid of natural vegetation. This facilitates recharge of ponded storm water, in contrast to the southern depressions, which are partly filled up with aeolian sand upon which a dense vegetation cover has become established, and the storm runoff is mainly intercepted and used in evapotranspiration.

There is a direct correlation between the extent of non-vegetated depressions and the northern fresh-water lens. Also isotope and geophysical surveys have confirmed the division of the country into separate groundwater provinces composed of water of contrasting quality and mode of occurrence. The total dissolved solids content of the northern groundwater varies from 500 to 2000 ppm while groundwater in the south is generally more brackish with total dissolved solids content of 4000 ppm or more. The northern fresh-water lens underlies an area of 2180 km, with a base of the lens or fresh-water/saline water interface at a level of approximately 100 m below sea-level. The total stored volume would amount to 2.5 km^3, assuming a specific yield of 1.5 per cent. By far the greater part of this fresh-water reservoir is situated below sea-level. During the past five years annual recharge has varied from about 2.8 to 21.8 million m^3 giving an average of 15.4 million m^3 in the north against 1.4 to 18.1 million m^3 with an average of 7.2 million m^3 in the south.

Agriculture

Agriculture is the largest consumer of groundwater although the quantities pumped for irrigation are uncontrolled and no effective legislation exists whereby private farmers are obliged to register and record pumping rates.

On the assumption that 35 per cent of the irrigated water infiltrates back to the groundwater reservoir as irrigation returns, the following net withdrawals were estimated by the Hydro-Agricultural Resources Survey project in 1972–73; the survey was repeated in 1976 with visits made to each farm and the results were as follows:

Groundwater withdrawals in Qatar in 1972–73 and 1976

	North Qatar (million m^3)	South Qatar (million m^3)
1972–73	26.60	2.09
1976	34.58	0.61

The majority of farms are concentrated in the northern and central part of Qatar as indicated by the limit of scattered agriculture in Fig. 13 in the area of

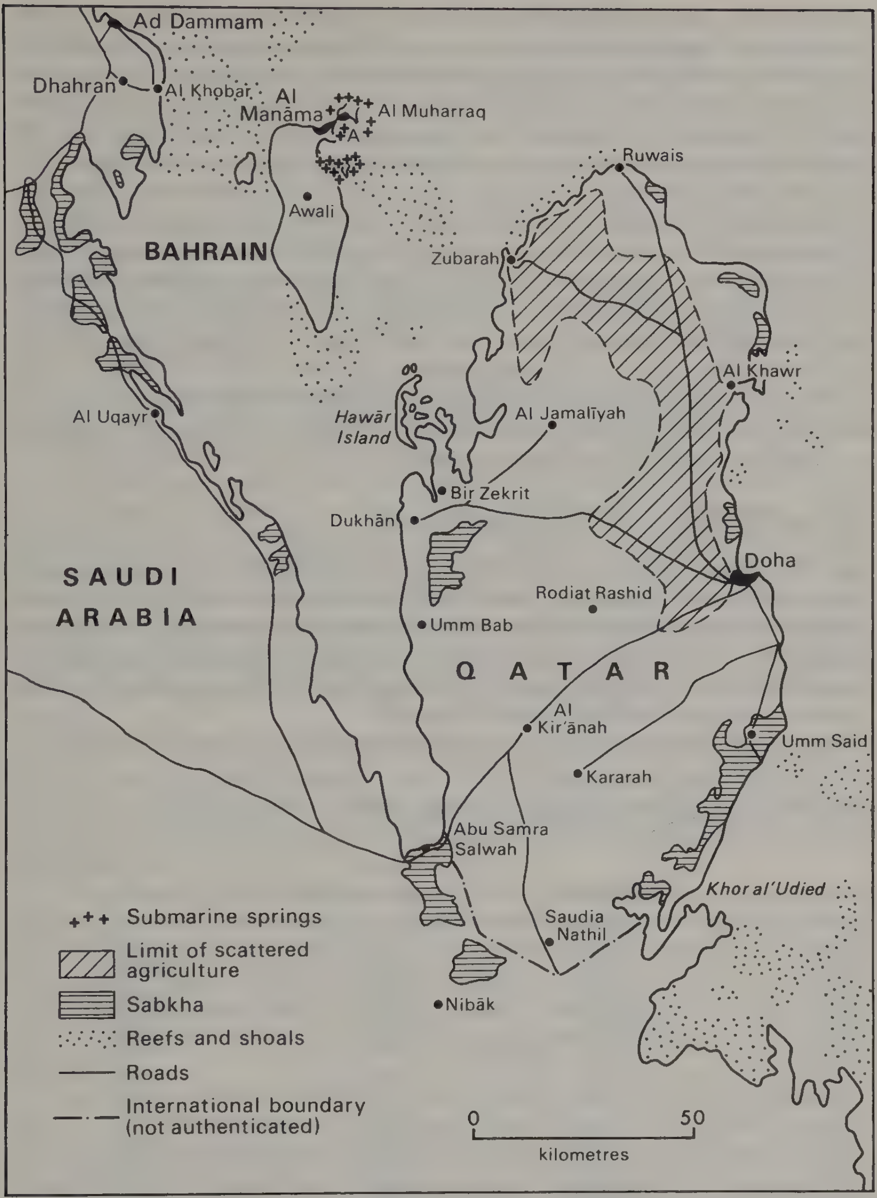

Fig. 13. Qatar and Bahrain showing the limits of scattered agriculture in Qatar and the location of sub-marine springs around Bahrain.

Source: Bahrain Water Resources Board.

the cultivated depressions. Here groundwater has been extracted from the fresh-water lens at over twice the rate of natural replenishment, while the quality is deteriorating at a rate of 5per cent/annum as a result of sea-water intrusion from the sides and the upward diffusion of deeper saline water. These processes are even accelerated by the influence of unnecessarily uneven water extraction. The agricultural policy is directed by landowners whose main revenues come from other sources, and they rent foreign labour to do the actual work. On many farms pumps and engines are old and are in need of replacement, and there is a reluctance on the part of the landlords to replace these capital items. Consequently there is a tendency to utilize the more effective pumps and overpump certain wells for prolonged periods resulting in excessive drawdowns and related proportional rise of saline waters from the base of the fresh-water lens, in accordance with the law of Ghyben-Herzberg.

The net consumptive use over the presently irrigated area of about 15 km^2 is according to the 1976 figures 2.40 m/annum. While the crop water requirements are estimated to amount to only 0.8 m/annum.

Sea-water distillation and potable water supply

Sea water distilled down to 100 ppm has provided the bulk of Qatar's domestic and industrial water needs for some time. This distillate is blended with groundwater from the well-fields before it is distributed to the municipal and industrial consumers. The Water Department of the Ministry of Electricity and Water is responsible for the supply of potable water and the Ministry maintains excellent records of the water production (see Table 10).

Desalination started with the production of distilled sea water in 1954, with a

Table 10. Potable water production in Qatar 1964–77 (million m^3)

Year	Distillate	Added groundwater	Total potable water
1964	2.40	1.59	3.99
1965	2.85	1.37	4.22
1966	2.79	1.29	4.08
1967	2.30	1.54	3.84
1968	2.93	1.64	4.57
1969	4.50	1.58	6.08
1970	4.74	2.07	6.81
1971	5.34	3.58	8.92
1972	5.14	3.84	8.98
1973	5.90	4.26	10.16
1974	8.80	4.33	13.13
1975	10.40	6.21	16.61
–	–	–	–
1977	23.67	–	39.00

capacity of 0.099 million m^3/annum which was blended with an equivalent amount of groundwater. In 1958 a new plant raised the total potable water supply to 0.713 million m^3. In 1963 the first two multi-stage flash evaporation units with the dual-purpose plant for electricity and fresh-water production at Ras Abu Aboud became operational. The total annual output of distillate 3.202 million m^3 while the total potable water supply was raised to 4.778 million m^3. Due to the startling deterioration in the groundwater quality an admixture of about 33 per cent of well-field water was required. By 1974 four additional units had been added to the Ras Abu Aboud station and the total capacity for distillation reached 12.443 million m^3. Because of the fluctuating demands for electrical power and water during the different seasons, and also because of the gradual rate of expansion of the distribution system, the actual production stays behind the fully installed capacity.

Table 10 shows the approximate production of *distillate* and *added groundwater* required to produce the total *municipal and industrial water supply* during the period from 1964 to 1977. All figures are in units of million m^3/annum.

The distillation plant at Ras Abu Aboud will be expanded by two more units bringing up the production at this plant to 19.08 million m^3 by early 1978. During the author's visit in December 1976 to the new dual-purpose multi-flash evaporation plant at Ras Abu Fontas, the first two units were just under operation for experimental production. Four other units were under construction while four more units were projected. Per unit the installed capacity will be 5 million gal of distillate/day and 50 Megawatts of electric power production. This will mean for the ten units together a distillate production of 82 million m^3/annum.

If electric power is needed distillate becomes a free by-product; on the other hand if water is required power is free. The most economic proportion in which distillate and electric power can be produced can only be determined during the experimental phase and seems to be a special characteristic of each individual plant.

The plants are fuelled by flare gas previously considered as a waste product and easy to be piped and applied. If oil would be used the maintenance cost would increase by about ten times. The costs per 1000 Imperial gal of the two first units at Ras Abu Fontas were estimated at between $US 1.5 and 2.0 or between $US 0.33 and 0.44/$m^3$. The plant will be commissioned in 1977 starting with a production of 13.27 million m^3 and gradually increasing to 53.09 million m^3/annum.

The total amount of potable water production will be for some time stabilized at the 1978 level partly on account of the closure of the original two units of Ras Abu Aboud (installed in 1963) and the closure of the well-field near to Doha. The latter will be partly replaced by a smaller quantity of brackish water for blending. Without further construction of other desalination plants than those mentioned above, and plant efficiency losses at 1 per cent/annum the Government of Qatar intends to increase the total production of distillate to meet the 1994 estimated demands of 100 million m^3/annum.

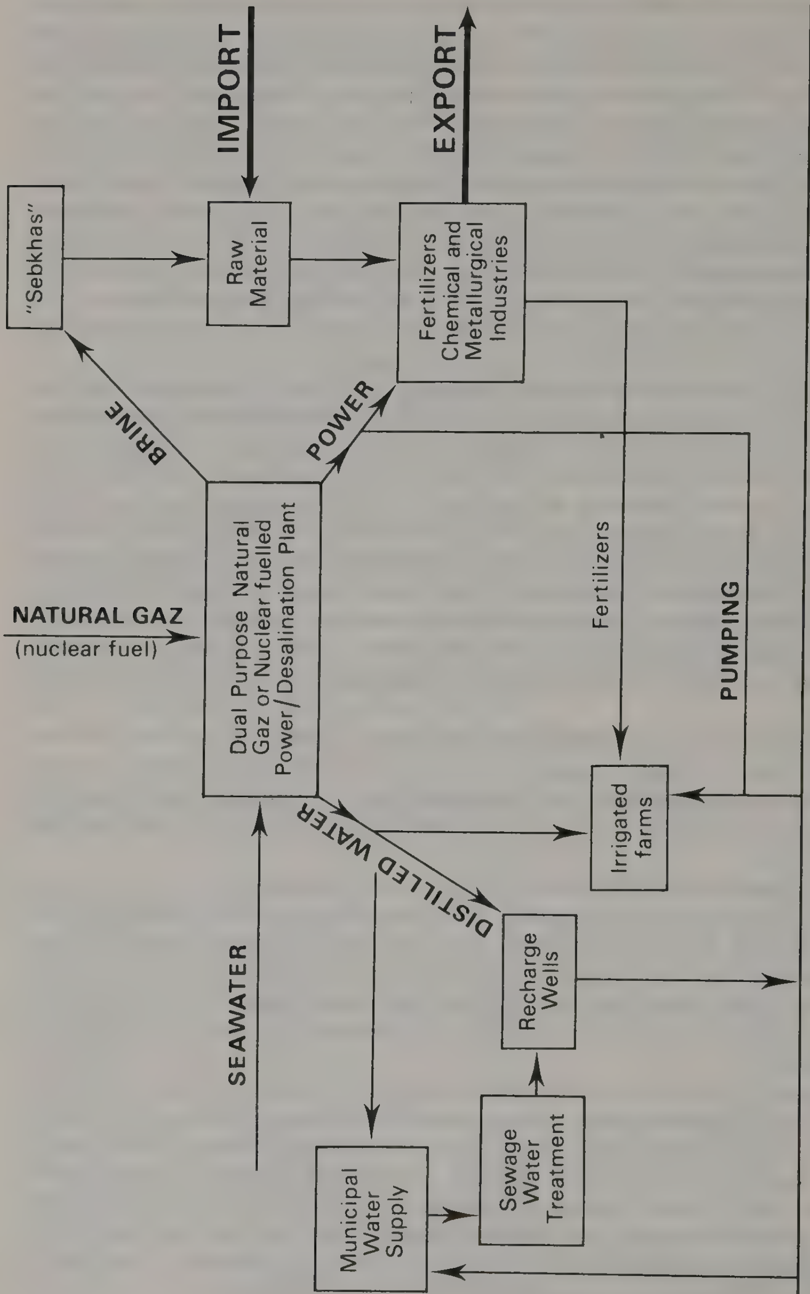

Fig. 14. A diagram of the functions of an agro-industrial complex.

Environmental consequences

The solution of the potable water problem in Qatar is a useful case study for the western Gulf Coast area and especially useful in revealing the environmental consequences of desalination. Sea-water normally reaches the desalination plant through an open channel protected by a screen. The temperature of the residual brine is about 5°C higher than the temperature of the entering sea-water and is returned to the Gulf. The temperature of the entering sea-water can rise in summer to about 38°C. Assuming that on the basis of the installed and projected desalination capacity the production of distillate in 1981 in the entire Gulf will amount to 700 million m^3 or 0.7 km^3/annum, and the Gulf waters have a salt content of 44 per cent, the quantity of salt dumped into the Gulf after water has been removed is roughly 30 million tons/annum, or almost 1 ton/sec.

The salt content of the Mediterranean is 38–39 per cent, and concentrations rise to 40–41 per cent in the Red Sea. In August each year the salt content rises to 42 per cent in the inner part of the Gulf (data by Wyrtki, 1971). Near Ras Abu Fontas in 1976 the reported salinity of the entering sea water was reported to be 44 per cent, while the sea water in the shallow triangle enclosed by the Saudi Arabian coast of Damman, Qatar and Bahrain reached as high as 50 per cent. Ongoing desalination on a large scale, and the lack of circulation are supposed to be responsible for this extreme figure.

As the sea-water exchange capacity of the Gulf with the Arabian Sea via the Straits of Hormuz seems to be inadequate to compensate for this effect (estimated residence time of the Gulf waters is about three years) increasing salinities may be expected with associated acceleration of the saline diffusion process along the Gulf coast. Several scientists have already expressed their concern over the matter. To cure the problem it has been suggested that the residual brines be piped to nearby sebkhas instead of returning them to the Gulf. In the sebkhas the sun will evaporated further the brines until all the salt has been precipitated. This would seem to be an acceptable solution, for the time being.

Table 11. Water balance in Qatar (all figures are given in million m^3/annum)

Ground water province	Estimated recharge	Net extraction			Depletion or increment to storage
		Agriculture	Domestic and industry	Outflow	
Northern area	15.45	33.99	4.53	7.00	−30.07
Southern area	7.19	1.20	0.10	3.00	+ 2.89
Total	22.64	35.19	4.63	10.00	−27.18

Water balance of Qatar

The water balance of Qatar has been averaged for the five years period up to March 1976 as shown in Table 11.

Pike and Parker (1976) estimated the depletion of the 2.5 km^3 northern fresh-water lens at a rate of 30 million m^3 or 0.03 km^3/annum giving a life of about 50 years, presuming that 50 per cent of that volume could be exploited at the present rates without further expansion of groundwater extraction. Because of the natural outflow shown on Table 12 it is impossible to reconstruct the accumulated rate of depletion of groundwater in a direct way. However, the

Table 12. Water balance for northern Qatar with the proposed artificial recharge project (million m^3/annum)

Year	Extraction			Recharge	Artificial recharge	Depletion or increment to storage
	Domestic/ industrial	Outflow	Agriculture			
1976	6.5	7.0	34	15.5	–	−32
1977	6.5	7.0	34	15.5	–	−32
1978	6.5	7.0	34	15.5	–	−32
1979	6.5	7.0	34	15.5	–	−32
1980	0.5	7.0	34	15.5	–	−26
1981	0.5	7.0	34	15.5	–	−26
1982	0.5	7.0	34	15.5	–	−26
1983	0.5	7.0	34	15.5	–	−26
1984	0.5	7.0	34	15.5	–	−26
1985	0.5	7.0	36	15.5	60	+32
1986	0.5	7.0	37	15.5	60	+31
1987	0.5	7.0	39	15.5	60	+29
1988	0.5	7.0	40	15.5	60	+28
1989	0.5	7.0	44	15.5	60	+24
1990	0.5	7.0	48	15.5	60	+20
1991	0.5	7.0	54	15.5	60	+14
1992	0.5	7.0	58	15.5	60	+10
1993	0.5	7.0	62	15.5	60	+ 6
1994	0.5	7.0	62	15.5	60	+ 6
1995	0.5	7.0	62	15.5	60	+ 6
1996	0.5	7.0	65	15.5	60	+ 3
1997	0.5	7.0	65	15.5	60	+ 3
1998	0.5	7.0	65	15.5	60	+ 3
1999	0.5	7.0	65	15.5	60	+ 3
2000	0.5	7.0	65	15.5	60	+ 3

Source: Parker and Pike (1976).

following indirect reasoning formed a basis for the approximate determination of this figure.

Agricultural activity is the major groundwater consumer, and is reckoned to have become a significant user as late as 1956, when the Agricultural Department was established. Before this period, coinciding approximately with the beginning of the larger scale extraction of groundwater for blending of distillate, the total outflow of the aquifer must have practically balanced the total recharge, or in other words a steady state condition prevailed in Qatar. So the annual average recharge of 22 million m^3 should have been discharged annually as total outflow along the coastal margins and by evaporation from coastal sebkhas and through coastal springs.

The sebkhas cover an area of 701.24 km^2 and the outflow of 0.022 km^3/annum would give a modest evaporation of only 31 cm/annum. The mean annual recharge was probably first exceeded by net withdrawals in the year 1966 (UNDP/FAO, 1974). Since then the 'mining' of the groundwater reservoir took place at rates which can approximately be reconstructed in a model from which the figures in Table 11 have been derived.

The southern aquifer with lower quality water shows a slight increment to storage of almost 3 million m^3/annum.

The gloomy prospects of Pike and Parker are almost certainly optimistic if one considers the projected water demands to meet the water needs of a fast growing population which will double by 1995. There is likely to be an associated increase in agricultural production and industrial development. In the meantime the Government of Qatar logically tries to reach a degree of self-sufficiency in staple food and vegetable production in the near future. Unfortunately the country has available only 276 km^2 of cultivable soils if irrigation could be provided. At present only 5 per cent of this area is under irrigation. Considering the amount of water used to cultivate this limited area of 15 km^2, it is clear that in spite of limited soil reserves water forms the limiting factor.

The proposed solution

Given the country's large financial assets and considering the serious water supply crisis which lies ahead if no preventive action is taken, considering also the abundance of natural gas as an economical power source for distillation, on a large scale, artificial recharge of distillate has been proposed as a solution to Qatar's water problem. A preliminary study of this proposal showed that an additional capacity of 60 million m^3/annum of desalination plant with distributing pipelines for the transportation of the distillate to batteries of injection wells at strategic locations within the northern fresh-water lens could solve the problem. This process would have the following advantages in that it would (Parker *et al.*, 1976):

(a) Minimize evaporation and transmission losses common to basin spreading recharge methods.

(b) Avoid silting problems of the recharge wells.
(c) Avoid contamination and undesirable chemical reactions between the injected pure distillate and the groundwater.

The artificial recharge project would achieve the following objectives:

(a) Compensate the groundwater reservoir for present over-exploitation.
(b) Utilize the fresh-water aquifer as a vast storage reservoir for future exploitation.
(c) Incrementally reverse the present deficit and thus replenish the cumulative depletion of recent years.
(d) Blend 'pure' water with the rapidly deteriorating groundwater thus rehabilitating the groundwater quality in general.
(e) Retard the rate of coastal salt-water intrusion and 'up-coning' from the base of the lens.
(f) Eventually stabilize declining water levels and if phased water management is practised, possibly lead to a situation of rising water levels.
(g) Allow for some phased expansion above present levels of improved irrigated agriculture.

Bearing in mind the present groundwater decline and accompanying problems it is estimated that an injection rate of at least 60 million m^3/annum would have to be attained before 1985. The actual construction of the plant(s), distribution network and injection wells plus the necessary feasibility studies have yet to be commissioned.

There are other options in water development to alleviate the present serious imbalance between recharge and extraction, but their impact will be insufficient to reverse and thus to control the present deteriorating trends. These development options as mentioned by Parker and Pike (1976) are the following:

(a) The induced recharge of storm water runoff by recharge wells and dikes to protect farms and farmland against flooding. The FAO Integrated Water and Land Use Project has demonstrated that in this way natural recharge could be increased by 30 per cent. Evidently the sinking of recharge wells in every depression in the country would be a prohibitive undertaking; in any event their effectiveness is ultimately dependent upon rainfall which has a high coefficient of variation. This measure carried out in the periphery of severely affected farms would moreover improve the groundwater quality.
(b) Replacement of groundwater extraction for blending of distillate in the northern province by extraction of the chemically inferior waters of the southern province. The recent advances in reverse osmosis technology in desalinizing brackish groundwater would allow a wide use of the modest quantities of groundwaters available in the southern province.
(c) It is estimated that approximately 25 million m^3 of treated sewage water could eventually be made available and probably within 20 years.

(d) Expert opinion has been obtained on the possibility of cloud seeding to increase natural rainfall. Apart from the uncertainties inherent in this technique it would probably only increase rainfall by 20 per cent and recharge by 3 per cent at considerable cost.

It is the great merit of the authors of *Groundwater Resources in Qatar and Their Potential for Development* (Parker and Pike, 1976) that despite considering a wide range of possibilities they demonstrate clearly their impotence to reverse the critical imbalance in the groundwater regime. In other words it is already too late to completely solve the problem with the help of the abovementioned development options, although they are not excluded as possible supporting measures amongst others in a groundwater management programme. They have had the courage, however, to present a revolutionary solution according to the following schedule for phasing of the activities.

Phase 1 covering period 1976–85:

(a) Domestic–industrial consumption of groundwater for blending of distillate will decline in 1980 to 0.5 million m^3/annum with the abandonment of some water well-fields.
(b) Extraction of groundwater for agriculture will not be increased beyond its present level of 34 million m^3/annum.
(c) Agricultural production can be significantly increased through improved irrigation efficiency. Traditional agriculture should be replaced by more capital intensive industrial type of farming, using methods such as cooled greenhouses, drip irrigation, plastic mulching and shading.
(d) Phase 1 will precede rapid expansion of irrigated agriculture scheduled for phase 2. Phase 1 will therefore include preparatory measures such as the amalgamation of some existing farm units, the linking of irrigation systems and laying out of new systems.
(e) Exploratory drilling and well testing in order to determine the basic aquifer parameters in northern Qatar, such as salinity changes with depth, specific yield, permeability and the volume of water in storage. Only in this way can the best locations be found for the injection wells, which would have to be sited in high permeability zones in order to accommodate the high injection rates required to minimize the number of wells.
(f) Feasibility studies and construction of new sea-water distillation plants, distribution network and injection wells.
(g) During this phase the net deficit in annual water balance will decrease from 32 to 26 million m^3.

Phase 2 covering period 1985–95:

(a) Domestic–industrial consumption of groundwater for blending with distillate will continue to stay at 0.5 million m^3/annum.
(b) Agricultural use of groundwater can be rapidly increased to a maximum consumptive use of 62 million m^3/annum.

(c) Artificial recharge will maintain its maximum injection rate of 60 million m^3.

(d) The groundwater balance will show a continued annual increment to storage. The net cumulative gain over ten years will amount to 174 million m^3 which would greatly redress the cumulative deficit of 258 million m^3 caused during phase 1.

Phase 3 covering period 1996–2000:

(a) Continued operation of the artificial recharge at its maximum level.

(b) The groundwater balance during this phase would continue to show a net annual increment to storage, but with the extraction being balanced at the end of the phase.

Phase 4 covering period 2000–25:

Follow-up to the previous phases. Achievements during phase 4 will clearly be indicated by the results of phases 1–3 and could conceivably include further development in groundwater conservation and management.

Table 12 illustrates the proposed measures.

It will be clear that the time element is critical and that any undue delay in implementing detailed investigations into a number of options and controls will bring about a crisis in the water supply situation within the next 15 years. The proposal would enable the conversion of revenue accrued from exported oil into a renewable national water resource that would be independent of variations in climate and allow for sustained development, diversification and moves toward domestic self-sufficiency. This would also solve the present investment problem facing the various oil-rich but almost waterless Gulf states whereby financial assets may be directly invested in a vital natural resource at home.

CONCLUSION

From the previous discussion it may be seen that the development of water resources in arid zones is becoming more and more an interdisciplinary problem with new specialized fields of study. At the beginning of the International Hydrological Decade it was still a matter of pure surface water and groundwater hydrology, while the current International Hydrological Programme is much more environmentally oriented. It is hoped that this trend will be carried through in the future and that water resources development policies dictated to a great extent by environmental factors will discourage policies which promote immediate short-term gains at the expense of the creation of a serious and perhaps critical imbalance in natural conditions. However, the adoption of such policies frequently requires a certain measure of financial prosperity which may be absent in poor countries.

The problem is not if water can be made available at a certain site, but rather, primarily, if it can be obtained cheaply enough to fit into the budget which handles it, and secondly, if it can be supplied in such a way so as to be assimilated as a new cultural amenity by the consumers.

To give an example: it is very difficult for the Egyptian fellah to adapt to the new idea that water in the Nile Valley has become a resource which should be used with care. Before the erection of the Aswan High Dam, the more water he used for irrigation, the more fertile silt was left behind on the cultivated lands. Today, the application of the same amount of water will wash the fertilizers out.

In pre-High Dam times the narrow cultivated Nile Valley and the strong seasonal fluctuating river levels guaranteed perfect natural drainage. The irrigation of virgin desert soils without carefully engineered drainage always results in water logging and salinity. It was, however, forgotten that the world of the Egyptian fellah was the Nile Valley and not the desert, and that different water management methods are required in the differing environments.

The introduction of a piped desalinated water distribution system in a desert area will affect life in a revolutionary way. The availability of costly good quality water within the immediate reach of a tap at home forms a contrast with the scarcity of the commodity which must be confusing for the unprepared water user. In all cases government agencies have an obligation to provide relevant guidance to introduce the new water resources. The changes brought about by such new resources should be as beneficial to the local population as they were originally meant to be. The mass media can render excellent service in this connection. Adaptations of legislative character should not be forgotten with water rates promoting the just use of water in the widest sense, and preventing unnecessary waste.

The introduction of new, large-scale technological 'hardware' can initiate profound alterations in the natural environment. 'Hardware' in this sense could be a large dam, a hydropower scheme like the Qattara project, a large canal like the Jonglei canal, large groundwater extraction projects such as at Kufrah, or a nuclear-powered agro-industrial complex. The introduction of such works and complexes should be accompanied by a series of adjusting technological and social measures to maintain the overall environmental equilibrium. In principle the situation should be avoided wherein man becomes the victim of his own intervention in nature, as has already happened too often and certainly not only in developing countries, for example in the extinction of the aquatic life in many European rivers, through pollution or the use of river water for cooling purposes.

The correction of these side-effects of the application of new technologies requires large investments. The problem for the authorities is to stay in control of the newly introduced changes by adapting the infrastructure through an up-to-date educational system.

If integrated development is the answer to overcome the constraints imposed by aridity, then integrated education should also be introduced early in the school system and in the universities. A mere hydrologist or scientist, without a notion of economics, is a danger for any society, more especially in a developing country. Universities could encourage advanced students, with different scientific backgrounds, to study projects of an interdisciplinary character. For instance a botanist, physicist, mechanical engineer and economist might collaborate in a greenhouse experiment, a hydrogeologist, agricultural engineer, soil scientist, climatologist and computer scientist in a land reclamation experiment. These activities should be conducted by multi-disciplinary committees of university staff, in order to make those in the academic world familiar with problems of practical integration. Study grants should be awarded with preference given to groups of students who want to study interdisciplinary problems. Their result would have more educational and scientific value than that of the same number of students each working on different subjects. A thesis representing a joint effort should be treated as one entity, and the risk of getting involved in such a joint enterprise should be left to the group of scientists who believe that their capabilities could be profitably integrated for the joint solution of scientific problems.

University training should be such that the students become aware of the principles of scientific and technological collaboration, which is a fundamental condition for successful integrated development. Fundamental research can be left to a great extent to the Western countries as it is time consuming and expensive. In the developing countries time and money can better be spent on the adaptation of new methodologies to the arid physical environment of the Arab world and to the special sociological circumstances of the region. Research should be carried out to study the economic, social and environmental impact of such methodologies.

In the applied sciences much research is needed, for instance in the use of

isotopes for limestone hydrology in arid and semi-arid zones, recuperation of evaporation losses, erosion and desert encroachment control. If the hydrology of karst systems could be better understood and better regulated technologically, these systems could be made beneficial for the surrounding population as a kind of natural water tower, with huge and easily accessible storage potential. If, in these systems, water levels could be lifted above the hidden groundwater divides, river flow could possibly be increased in the inland direction of coastal limestone massifs.

The introduction of large nuclear-powered agro-industrial complexes as an extreme case should be compared with the medical technology of organ transplantation. A fundamental and most crucial problem to overcome was the natural tendency of the host body to reject the new insertion. In order to overcome this rejecting impulse and even to make the host body assimilate the organ in such a way that they would form together one organic entity, fundamental physiological research had to be carried out. It is exactly this kind of research which leads to the acceptance of the new technological transplantation in the developing host country. This essential scientific socioeconomic contribution is needed to assure the total functional and cultural integration of this potentially alien complex.

Like any comparison, this one is faulty in the sense that, in the case of water resources development, no existing 'organ' is replaced. Here the introduction of an essentially new concept is involved. Since shortage of water causes the fundamental problem in arid lands, the complex should never replace existing natural water resources but should always be complementary to them.

Finally, it should not be forgotten that to apply successfully a method related to water resources development requires more skills and exactitude under arid conditions than under other climatic conditions. Only the *wise use* of modern technology can turn it into a blessing.

Cairo
August 1977

ANNEXE

COUNTRY REVIEWS OF ENVIRONMENTAL AND HYDROLOGICAL INFORMATION

Algeria (La Republique Algérienne Démocratique et Populaire)

Area: 2 381 741 km^2
Cultivable land or 17 per cent of total surface: 424 480 km^2
Productive land: 200 000 km^2
Desert: 1 200 000 km^2
Length of sea coast: 1200 km
Highest mountain: about 2700 m above sea-level
Population
1973: 15 759 570
1977: 17 800 000
Growth rate 1966–73: 3.2 per cent
Capital: Algiers (population in 1973, 1 500 000)

Soil conservation as a protection against erosion has a high priority.

Annual precipitation

Coastal zone: rain increases from Oran 400 mm to Constantine 1000 mm
Atlas Tellien: rain and snow 400–2000 mm
'Hautes Plaines Telliens': more than 400 mm (snow) in east
'Hautes Plaines Steppique': less than 400 mm in west
'Atlas Saharien': rain and snow up to 1000 mm

The 'Atlas Saharien' forms the water divide between the Sahara and semi-arid and humid area in the north with a total surface area of 293 750 km^2. On the 'Hautes Plateau' a green belt is being established of 1500 km in length and 20–40 km wide to protect an area in the north of 35 000 km^2 against desertification.

Annual groundwater potential north of 'Atlas Saharien' is 1.382 km^3 of which in 1973 about 50 per cent or slightly more than 0.616 km^3 was used. Although this seems favourable, the area around Algiers has reached almost its limit for groundwater consumption (83 per cent in 1973, of effective rainfall).

In 1970 there were 17 dams.

The precipitation on the southern slopes of the 'Atlas Saharien' drains towards the northern Sahara, consisting of the western basin with altitudes between 200 and 700 m above sea-level an area of 280 000 km^2, which drains towards the south, and the eastern basin draining to the east (Golfe de Gabés)

with altitudes between −40 and 400 m, which occupies inside Algeria 420 000 km^2. Annual rainfall in the northern Sahara is less than 100 mm, but exceptionally, during three days in November 1969, it reached 200–300 mm in the extreme eastern (Tunisian) part of the basin.

The northern Sahara including the 80 000 km^2 of Tunisian territory, receives on average 0.851 km^3 recharge as computed for the period between 1950 and 1970, mainly from the southern slopes of the 'Atlas Saharien'. Groundwater utilization in this period was 1.021 km^3. The excess of withdrawal over recharge is possible because of the enormous groundwater reserves stored in the underlying aquifers estimated to be about 60 000 km^3. If the irrigated area were to be increased from the present 500 to 1000 km^2, the water use would increase to over 3 km^3/annum. This is expected to happen by the year 2000.

Petroleum production started around 1960. Algeria has large petroleum and even more gas reserves.

Iron ore reserves: 1 million tons.

References: ALESCO (1977), DEMRH (1973e, f), UNESCO (1976).

Bahrain (State of Bahrain)

Area: 622 km^2
Irrigated area: 37 km^2 or 6 per cent
Population
  1973: 236 000
  1977: 250 000
Growth rate 1970–73: 1.8 per cent
Bahrainis: 82 per cent
Capital: Manama (population in 1971, 89 399)

For water supply the country depends entirely on the deep aquifers and desalinated water since there is not surface water.

Annual precipitation

Rainfall: 75 mm
Groundwater production: 0.199 km^3

(The quality is high but the water table is dropping markedly.)

Desalinated water	8.3×10^6 m^3/annum, in operation
	24.7×10^6 m^3/annum, under construction
Total production of desalinated water	33.0×10^6 m^3/annum in 1981 or 0.033 km^3/annum
Actual water use	
Agriculture	166×10^6 m^3/annum
Domestic	20×10^6 m^3/annum
Industry	13×10^6 m^3/annum
	199×10^6 m^3/annum or 0.199 km^3/annum

Future water demand:

Agriculture	$126 \times 10^6\,m^3$/annum
Domestic	$41 \times 10^6\,m^3$/annum
Industry	$15 \times 10^6\,m^3$/annum
	$182 \times 10^6\,m^3$/annum or $0.182\,km^3$/annum

Before 1930, Bahrain's economy depended mainly on pearl fishing and the transit trade. Since then petroleum production and refining are most important. In 1970, maximum production of 28 million barrels of crude oil was reached, and since that time, production is declining gradually. It has been estimated that the current rate of production will be possible for about ten years. Bahrain operates one of the world's largest petroleum refineries and only exports refined oils. There exist large reserves of gas.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

Egypt (Arab Republic of Egypt)

Area: 1 001 449 km^2
Irrigated land: about 30 000 km^2
In 1985 it is anticipated that 7000 km^2 more irrigated land will be available
Coasts have a total length of: 2396 km
 Mediterranean: 995 km
 Red Sea: 1941 km
Population in 1977: 39 000 000
Growth rate: 3.2 per cent
Capital: Cairo (population 8 000 000)
Alexandria: population over 2 000 000
Half of labour force in agriculture

Annual precipitation

Winter rainfall along Mediterranean, the wettest part of the coast, receives 184 mm/annum. The remaining part towards the east (Port Said) receives 75 mm/annum or less. Rainfall decreases rapidly inland. Cairo receives 18 mm/annum. Any other part further south may receive rain only every second or third year.

Hot dry sand storms (khamassin) mainly in spring. During spring and early summer, early morning fog in Lower Egypt. The Nile which is 1530 km long in Egypt, provides irrigation waters, of which about 46 km^3/annum is applied to the lands. 16 km^3 are lost in rivers and canals downstream of Aswan.

Water consumption is about 16 000–14 000 m^3/acre/annum. The Ministry of Irrigation will decrease consumption to 8000 m^3/acre/annum. Normally drainage Research is investigating ways and means of mixing irrigation and

drainage waters in order to increase the rate of water utilization. The salt balance is becoming increasingly important as a negative factor in agricultural development.

Outside the Nile Valley, the large depressions in the waterless plateau of the Western Desert, form the only cultivable regions, because of the artesian groundwaters from the Nubian Sandstone aquifer, which reach the surface in the depressions. The largest depressions are: Kharga, Dakhla, Farafra, Baharya, Siwa and Qattara. The elevation above sea-level of the depressions declines in the same succession to far below sea-level in the case of the Qattara depression in the north. Only the Qattara depression, with its deepest point of 133 m below sea-level, is not inhabited by a sedentary population.

The highest elevations are found in the Red Sea Hills, which exceed 2000 m above sea-level, while altitudes of about 2000 m occur in the Jabal Uweinat, where the borders of Libya, Sudan and Egypt meet.

Non-renewable resources: Petroleum, iron ore, phosphate, lead, zinc and salt.

Iraq (Republic of Iraq)

Area: 438 446 km^2
Irrigated area: 36 800 km^2
Rain-fed agricultural area: 40 000 km^2
Total cultivated area: 76 000 km^2
80 per cent of irrigated land affected by salinity
Waterlogged land: 10 000 km^2
Population
1973: 10 413 000
1977: about 12 000 000
Growth rate 1970–73: 3.3 per cent
Capital: Baghdad (population, 3 250 000)
Almost half of the population are engaged in agriculture.

Annual precipitation

(a) Zagros mountains (26 000 km^2) with the highest peaks of 3700 m consist mainly of limestone. Mean annual precipitation (also as snow) 500–1000 mm which serve rain-fed agriculture.
(b) Foothills, south-west of Zagros mountains, receive 300–500 mm/annum and also support rain-fed agriculture.
(c) The Jazira, between the Euphrates and Tigris south of the foothills sloping gently south-east from 500 m at the foot of Jabal Sinjar on the Syrian border and sloping from 260 m near Abu Kemal in the west to 83 m above sea-level near Falluja. Except for limited rain-fed agriculture in the north, the region is used for grazing and livestock. Areas (b) and (c) cover 65 000 km^2.

(d) The lower Mesopotamian plain (90 000 km^2) south of Ramadi (on the Euphrates) and south of Tikrit (on the Tigris). Mean annual rainfall 150 mm. Irrigation mainly with river water. Salinity problems affect 50 per cent of irrigated lands. In the south are the saline marsh lands.

(e) The desert (265 000 km^2) west of Euphrates receives an annual rainfall of less than 100 mm. It slopes from south-west to north-east.

Surface water

Euphrates (Hit)	31 820 km^3/annum
Tigris (Mosul)	23 210 km^3/annum
Tributaries of the Tigris	29 455 km^3/annum
Total	84 485 km^3/annum

Average annual available surface water calculated by Ubeli from 1931 to 1969 is about 84 km^3.

	Length in Iraq (km)
Euphrates	1152
Tigris	1418

The Shatt el Arab is 110 km long, from the Gurmet Ali confluence to the mouth of the estuary at Fao on the Arabian Gulf.

The major part of the discharge of Euphrates and Tigris is absorbed in enormous lakes and swamps through the tidal influence of the Gulf. Only a part discharges through the Shatt el Arab to the Gulf, while much is evaporated from the lakes and swamps.

Flood control is executed through diversion of flood waters to storage reservoirs such as Lake Al-Habbaniya, the Abu Dibbis depression and the Tharthar depression. The latter alone has a storage capacity of 80 km^3.

Energy supply

The presently projected needs are about 1300 Megawatts. Half of this may have to be supplied by hydropower. At present, three dam sites are available for hydropower generation: Samarra (Tigris), Dokan (Lesser Zab) and Derbendi Khan (Diyala). Only the Samarra hydropower plant is in operation.

Annual groundwater production 1.2 km^3 with salt content of 500–3000 ppm.

Water use per year
- Irrigation: 40.00 km^3
- Domestic purposes: 0.58 km^3
- Industry: 2.24 km^3

Future water demand in 1995
Irrigation: 52.00 km^3
Domestic use: 3.50 km^3
Industry: 11.90 km^3

Length of sea coast 60 km.

Petroleum activities started in 1888, and commercial petroleum production has existed from the beginning of the century.

Non-renewable sources: petroleum, sulphur and phosphate.

References: National Report of Iraq (1976), UNDP/UNESCO (1975).

Jordan (Hashemite Kingdom of Jordan)

Area including the Dead Sea: 96 188 km^2
Total area East Bank: 88 800 km^2
Area Dead Sea: 755 km^2
Cultivable area: 12 500 km^2 (13 per cent)
Irrigated area: 400 km^2
Rain-fed agriculture: 5170 km^2 (of which 37 per cent is fallow)

Note: The fallow area rises to 49 per cent in areas with 200–250 mm of rainfall; it drops to 10–15 per cent in the rainfall zone with more than 350 mm.

Population
1973: 2 516 000
1977: 2 800 000
Population in 1973 on the East Bank: 1 800 000
Growth rate 1970–73: 3.4 per cent
Capital: Amman (population, 7000 000)

44 per cent of the total population lives in urban areas and over 50 per cent in rural areas.

Relief

Mountainous regions in west; desert or semi-desert in east. The mountainous region consists of two highland areas with altitudes varying from 600 to 1000 m. In between those areas is the rift valley which drops to a depth of 400 m below sea-level in the Dead Sea.

Annual precipitation

Precipitation: rainy season from October to April
Western highlands: precipitation 300–700 mm (also snow)
Eastern highlands: precipitation 300–600 mm (also snow)
Jordan valley (irrigated area): 300–600 mm
Southern desert: rainfall less than 250 mm
Eastern desert: rainfall less than 150 mm

Areas with rainfall less than 200 mm/annum are unsuitable for crop farming. This is 80 per cent of the land or 75 000 km^2 which is used for rangeland and grazing for 854 000 sheep, 525 000 goats and 13 000 camels. Ploughing of this land leads to heavy wind erosion.

Annual surface potential is 0.85 km^3 from the eastern tributaries of the River Jordan such as the Yarmouk river. Groundwater production was 0.165 km^3 in 1975. Groundwater comes from many types of rock, limestone chert, dolomite, basalt, sandstone and alluvial gravel, yielding from 5 m^3/hr to 300 m^3/hr.

About 1 000 000 people are now concentrated in the urban area of Amman Zerga, which occupies the upper watershed of the river Zerga. This area is underlain by the extensive Amman Wadi Sir aquifer. This carbonate rock aquifer is still considered to be under-exploited and with proper management could probably provide an even larger part of the total supply. Measures must be taken, to protect the aquifer against pollution from household septic tanks and industrial wastes. The aquifer could also provide underground storage space for artificial recharge through injection wells of storm runoff, treated sewage effluent of Amman and any other available surplus water. The quality of the groundwater is high but is subject to contamination.

Annual water use
- Irrigation: 0.375 km^3
- Domestic purposes: 0.004 km^3
- Industry: 0.006 km^3

Estimated annual water demand in 1990
- Irrigation: 0.465 km^3
- Domestic use: 0.060 km^3
- Industry: 0.030 km^3

Non-renewable resources: phosphate in the Dead Sea area as well as potash and magnesium, some copper, manganese and oil shales.

References: Durbaum *et al.* (1972), FAO (1975), Mudallal (1973), UNESCO/IESO/UNEP (1976).

Kuwait (State of Kuwait)

Area: 17 818 km^2 of which ten offshore islands occupy 1000 km^2 Coast on Arabian Gulf is 300 km long

Land flat, highest region in the south-west corner of the country about 400 m

Irrigated area: 9.40 km^2 or 9400 ha

Population
- 1973: 943 766
- 1975: 991 390 (of which 48 per cent are Kuwaitis)
- 1977: 1 000 000

Annual precipitation

Rainfall varies between 23 and 206 mm with an annual mean of 118 mm (1952–71).

Duststorms in May, June and July.

No permanent rivers.

Irrigation depends on water from deep aquifers

Rawdhatain aquifer:	300–1300 ppm	yielding $13 \times 10^6 m^3$ or
Sulalyah aquifer:	2500–5000 ppm	$0.013 km^3$ in 1974
Desalination		
In operation	$102.9 \times 10^6 m^3$	
Under construction	$66.4 \times 10^6 m^3$	
Estimated total in 1980	$169.5 \times 10^6 m^3$ or $0.1695 km^3$	

The utilization of treated sewage effluent of $0.029 km^3$/annum is now being tested for agricultural uses.

Annual water use for irrigation gardens and household: $0.065 km^3$
Estimated annual water demand in 1995:
Agriculture: $1.150 km^3$
Domestic: $1.730 km^3$
Industry: $0.050 km^3$

Petroleum revenue is the most important source of Kuwait's income.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

Lebanon (Republic of Lebanon)

Area: 10 400 km^2
Plains: 30 per cent
Mountains: 70 per cent
Cultivable land: 47 per cent
Cultivated land: 3910 km^2
Irrigated land: 640 km^2
Area covered by forest: 23 per cent
Arid region: 30 per cent
Steep rocky mountains: 6500 km^2, used for grazing
Population in 1974: 2 701 774 (of which 800 000 were foreigners)
Growth rate: 3.1 per cent
Capital: Beirut
Population: 700 000
Urban population: 58 per cent

Two mountain chains run parallel to the coast: the western Lebanon mountains with highest peaks at 3083 m in the northern regions dipping towards the

south. The eastern Anti-Lebanon mountains have peaks of 2800 m in the south. The Bekaa rift valley dips from Baalbek (1100 m) to the north (Orontes catchment) and to the south (Litani catchment).

The coastline is 220 km long.

Annual precipitation

Rain and snow fall between October and May.

On the coastal plains: 800 mm
On the Bekaa plain
  South: more than 800 mm
  North: less than 300 mm

In the mountains precipitation falls mainly in the form of snow, depending on altitude. Precipitation ranges from 900 to 2000 mm.

Annual surface water potential: 3.8 km^3

  Of the total amount of atmospheric water only 5 per cent is used.
Groundwater production: 0.05 km^3
Actual annual water use
  Irrigation: 0.647 km^3
  Domestic use, Industry: 0.094 km^3
Estimated demand in the year 2000
  Irrigation: 3.180 km^3
  Domestic use, Industry: 0.600 km^3
Non-renewable resources: phosphate, lignite, pyrites, lithium.
References: Economic Commision for Western Asia (1976), FAO (1975), UNESCO (1976).

Libya (Socialist People's Libyan Arab Jamahariyah)

Area: 1 754 000 km^2
Cultivable area: 20 900 km^2
Rain-fed cultivated area: 5510 km^2 which should increase to 8080 km^2 by 1980
Irrigated area: 1680 km^2 which should increase to 2680 km^2 by 1980
Population
  1973: 2 257 037
  1977: *c* 2 750 000
Growth rate
  Libyan Nationals (1964–73): 4.2 per cent
  Non-Libyans (1964–73): 17.1 per cent
Capital: Tripoli (population, 800 000)

Irrigated agricultural development projects envisaged in 1983: 5000 km²
Afforested sand-dune area from 1952–76: 440 km²
Afforested land from 1952–76: 440 km²
Area of dune fixation: 440 km²
Length of sea coast: 1980 km

Annual precipitation

Rainfall occurs between March and October and is erratic and scanty. The average annual rainfall in Tripoli calculated over 25 years is 300 mm and exceeds 500 mm east of Benghazi on the Jabal Akhdar. The average relative humidity along the coast is about 55 per cent.

The average annual rainfall drops to below 100 mm at a distance of more than 20 km from the coast and becomes even 10 mm or less in the east and in the deserts.

Utilization of surface waters is in rain-fed areas which have been extended by various dams to provide flood protection and conservation of occasional discharges of intermittent wadis to enable water supply to new farms. Examples: Wadi Ki'am, El Qattara Valley, Sammalus and Zuba Valleys, Hisa and Magenin projects.

Utilization of groundwaters

In the northern coastal areas the irrigated area was extended on the basis of private investments by individual farmers. For this purpose, groundwater was used which by 1968 showed severe signs of over-exploitation. In some regions for instance 20 km south of Tripoli groundwaters were falling over 1 m a year. The situation continues to deteriorate while sea-water encroachment decreases the quality of the groundwater in the north.

These experiences along the coast made the Government decide to initiate agricultural schemes in remote desert areas based on fossil groundwater such as at Kufrah. The Kufrah Production Project is a capital intensive sheep breeding and fattening scheme and the Kufrah Settlement Project is designed for a much more complex agricultural development with farmers living in small hamlets to control the irrigation water and the intensive production of field and tree crops in nearby fields.

Water desalination has started.

Petroleum production started in 1961. About 70 per cent of the oil reserves are consciously spent on the diversification of the economy.

References: ALESCO (1977), Allan (1975), Allan *et al.* (1975), UNESCO (1976).

Morocco (Kingdom of Morocco)

Area in 1973: 446 550 km^2
Cultivable area: 75 000 km^2
Grazing area: 76 500 km^2
Area covered with forests: 52 350 km^2
Irrigated area: more than 4000 km^2 to be increased to 10 000 km^2 by 2000
Length of coastline: 1750 km
  On Mediterranean: 450 km
  On Atlantic: 1300 km

Three mountain chains cross the country:

Rif Mountains in the north: highest point 2456 m
Middle Atlas: highest point 3326 m
High Atlas: in the south highest point 4165 m

Annual precipitation

The average annual precipitation is about 150 km^3 of which about 25 km^3 is effective. The effective part of the precipitation falls in one to four months according to the region. A large part falls in the form of snow which is so far poorly recorded and observed.

25 per cent of the surface area receives more than 600 mm
25 per cent of the surface area receives 300–600 mm
50 per cent of the surface area receives less than 300 mm

Surface water

17 km^3 is discharged as flood waters while 3 km^3 provides the base-flow outside the flood period.

The Middle Atlas alone is the source of the most important rivers, the Sebou, Oum-er-bia, Loukkos, Moulouya, Ten rift, Bou Regreg and Draa providing together an annual discharge of 15.5 km^3.

The total storage capacity in storage reservoirs is 7.2 km^3.

Groundwater

Of the annual groundwater recharge of 9.5 km^3, 4.7 km^3 are exploitable. The quality of the groundwater is an important problem.

Water for domestic use amounts to 1.5 km^3/annum and is expected to become 9 km^3 by the year 2000.

Action taken or foreseen for improvement

A revision of the law on water use, formulated over 50 years ago, is now being executed by a study group of the Ministry of Public Works. The first water

balance of the country was calculated in 1967. The authorities' objectives at present are to make the most effective use of the available waters to ensure the availability of the water resources at the time of requirement, and to plan utilization and re-utilization as a function of the existing needs which can successfully be satisfied downstream. An efficient snow observation and recording system, non-existent so far, should be established.

Experimental catchments will be created in order to determine accurately the percentage of runoff and infiltration of the total precipitation and the suspended load of the runoff water as a function of rainfall distribution, geology, geomorphology and vegetation cover. The objectives of this experiment will be to obtain representative figures for extrapolation over large parts of the country for forecasting purposes.

Recycling of infiltrated irrigation waters and waste waters after purification have to be effected.

Degradation of the soil through erosion is a very serious problem. Storage reservoirs contribute to the regulation of torrential wadis and curb the suspended load content. But the existence of the storage reservoirs themselves is in danger. The silting up process reduces their life if no action is taken. Special reservoirs for sediment deposition need to be made upstream, and wadi banks and gullies have to be stabilized through afforestation. Recharge of groundwater as a means of storage will be given high priority especially in the south where the potential evaporation is high.

Non-renewable resources: in succession of their importance are the following: phosphate, anthracite, iron ore, manganese, lead, copper, tin, silver, nickel, cobalt, petroleum and natural gas.

References: ALESCO (1977), County Review of Morocco (1976), Direction de l'Hydraulique (1973), UNESCO (1976).

Muscat and Oman

Area: 212 457 km^2
Less than 1 per cent is under cultivation
Irrigated area: 360 km^2
Length of coast: 1700 km
Population in 1973 was estimated at 722 000 inhabitants
Growth rate 1970–73: 3.2 per cent
Muscat population: 40 000
80 per cent of the population is engaged in agriculture.

Annual precipitation

The northern mountains, among which the best known is the Jabal Akhdar (Green Mountains) with an altitude of 3170 m, forms a major source of water in the country.

Rain falls in December, January and February. Runoff drains towards the coastal plains covering 9000 km^2 on the Batinah coast (from Muscat to the north) which contains 40 per cent of the cultivated area.

The southern mountains rise to 1200 m above sea-level and receive monsoon rains in the summer.

Average annual rainfall varies according to the region from 40 to 180 mm.

Surface water

There are no lakes and no rivers, but there are falaj (a man-made channel of water originating from underground in mountainous regions) and springs.

Available surface water: 10×10^6 m^3/annum or 0.010 km^3/annum
Groundwater resources: (exploitable) or 0.650 km^3/annum
Capacity of desalinated water: 2×10^6 m^3/annum or 0.002 km^3/annum
Annual water use
  Irrigation: 0.420 km^3
  Domestic purposes: 0.010 km^3

Petroleum production started in 1967.

The geology in Oman seems to be promising for economic mineral deposits like copper and chrome. The occurrence of iron ore in exploitable amounts is probable as well as magnesium, manganese and nickel.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

Qatar (State of Qatar)

Area: 10 600 km^2
Peninsula: 180 km long and 85 km wide
Irrigated area: 19.75 km^2 out of an area with cultivable soils of 296 km^2
Population in 1975: 135 000
Indigenous population in 1975: about 52 000
80 per cent of the population lives in and around Doha the capital
Growth rate: 4 per cent

The highest point of the rather flat country is 103 m above sea-level.

Annual precipitation

Rainfall is very irregular, but it amounts on average to 50 mm/annum. An example of the irregularity was the 68 mm rain which fell in April 1972 in just over one hour over a small storm area of 3000 km^2 of northern Qatar.

The following four seasons can be distinguished:

November–mid-February: main growing season (temperature 7–30°C)
Mid-February–Mid-May: rapidly rising temperatures and increased wind speed

Mid-May–July: very high maximum temperature, 42°
August–October: Sudden onset of greatly increased relative humidity whilst temperature remains very high (the most trying part of the year)

Groundwater resources

Total estimated groundwater reserves in the northern groundwater province 2500 km^3 with an area of 2180 km^2, mostly located below sea-level. 850 depressions functioning as interior drainage catchments from 0.25 to 45 km^2, provide a total surface of 6942 km^2, through which the storm water runoff recharges the fresh groundwater lens floating on the deeper saline aquifer.

On the basis of five years of reliable records, a provisional water balance has been made (all figures are expressed in $10^6\,m^3$/annum, i.e. $10^{-3}\,km^3$/annum).

The northern groundwater province with water quality of between 400 and 2000 ppm receives a recharge of 15.45; a net extraction of 37.52 plus 7.00 outflow into the coastal sebkhas or sea = 44.52.

Depletion of the northern aquifer is 30.07.

The southern groundwater province with waters between 2000 and 6000 ppm receives a recharge of 7.19; a net extraction of 1.30 plus 3.00 natural outflow into the coastal sebkhas or sea; increment in storage is 2.89.

At the present rate of groundwater extraction, the effective life of the northern aquifer is estimated to be 25–30 years.

	$10^6\,m^3$/annum
The present annual water consumption	
Agriculture	35.2
Domestic	16.6
The present total water consumption	51.8
About 300 pumped water wells withdraw	40.2
While desalination provides	11.6
Total	51.8

Land ownership is considered as recreation which is illustrated by the non-commercial approach to farming. Agriculture is executed exclusively by foreign labour.

Farming was not an established occupation in Qatar. This can be shown by the following table:

Number of farms in past years

1940	1950	1960	1970	1976
No farms	A few	119	411	270 (1975 ha)

Desalinated sea-water was introduced in 1955 and gradually it has provided the bulk of domestic and industrial water requirements.

The existing desalination capacity in 1975 of 10.4 will, in 1977, be increased by 18.6, providing a total installed capacity of 29.0 (all figures expressed in $10^6 m^3$/annum).

Petroleum production started from 1939 onwards. In the last five years also considerable offshore gas fields have been found.

It has been proposed that the vanishing fresh-water lens of the northern province be restored by artificial recharge using desalinated sea-water (see page 89). Also the rising domestic consumption could make available an increasing amount of treated sewage waters for artificial recharge, or directly for irrigation.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

Saudi Arabia (Kingdom of Saudi Arabia)

Area: 2 590 000 km^2
0.1 per cent of total area covered with fertile soils
Irrigated area in 1971: 1780 km^2
Population in 1973: 8 448 000
Growth rate 1970–73: 2.9 per cent
Population in 1977: about 10 000 000
Of the total labour force in 1975: 1 522 100–28 per cent work in agriculture

Length of the western coast along the Red Sea and Gulf of Aqaba is 1770 km.
Length of eastern coast along the Arabian Gulf is 483 km.

Average annual rainfall distribution

The coastal plain along the Red Sea with a width of 65 km in the south, narrows to 16 km in the north and receives on average 250 mm of rain/annum. A mountain range with peaks exceeding 2700 m and precipitation up to 400 mm, separates the coastal plain from the Najd plateau. This plateau with elevation from 1200 to 1800 m above sea-level, is located in the centre of the country and receives 85–110 mm. The plateau slopes gradually towards the Arabian Gulf in the east with rainfall from 50 to 70 mm, where the oil fields are situated. The northern region received 80–120 mm.

Surface waters

These occur only in the form of occasional storm runoff and total about 2200 km^3/annum.

Groundwater resources

28 000 wells produce an estimated 1.723 km^3/annum in the eastern part from the Tertiary limestone aquifers.

Aquifers containing important groundwater reserves are:

Wajid aquifer: estimated reserves 1000 km^3, quality 530–820 ppm
Minjur aquifer: quality good
Saq aquifer / Tabouk aquifer } seem to have promising characteristics

Desalinated water

In 1965 the Saline Water Conversion Corporation was established. Studies were undertaken of various processes for desalination of sea-water. As a result, the multi-flash distillation process was selected for large-scale production of fresh water, while if justified, the preference went to the dual purpose plants producing electric power and fresh water. In 1976, five plants were in operation, while 28 more are planned, all using flare gas or fuel oil as a power source.

The capacity of desalinated water in operation is	0.036 km^3/annum
The capacity of desalinated water under construction is	0.129 km^3/annum
Total capacity installed in 1980 will be	0.165 km^3/annum

The present annual water consumption
- Agriculture: 1.350 km^3
- Domestic: 0.830 km^3
- Industry: 0.150 km^3

The future water demand in 1980 will be:
- Agriculture: 1.800 km^3
- Domestic: 1.048 km^3
- Industry: 0.250 km^3

Petroleum production started in 1938.

Other non-renewable resources: gas for desalination plants and gold, copper, iron and lead in the central and western part of the country.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

Sudan (Democratic Republic of the Sudan)

Area: 2 505 813 km^2
Desert and semi-desert: 1 200 000 km^2
Tropical rain forest: 500 000 km^2
Cultivable area about: 800 000 km^2
Area used as rangeland: 230 000 km^2
Area used as cultivated land: 70 000 km^2
Irrigated area in 1978: 18 000 km^2 out of an irrigable area of 42 000 km^2
Population: about 17 000 000
Growth rate: 3 per cent

Khartoum: 800 000
88 per cent of the population is in rural areas
25 per cent of the rural population is nomadic; they own 95 per cent of the livestock.

Livestock

Livestock population in 1972:
Cattle: 13 058 000
Sheep: 11 923 000
Goats: 7 817 000
Camels: 2 960 000

Length of the Red Sea coast: 864 km

Average annual rainfall distribution

The rainfall varies from 23 mm in the north to 1800 mm in the south. Isohyets are oriented east–west and aberrations are only caused by mountains. These mountainous areas are Darfur with the Jabal Marra reaching 3024 m, which receives 1000 mm; the Sudanese Red Sea Hills with many tops exceeding 1500 m, receive from 25 to 150 mm; the Kordofan mountains exceeding 1000 m, receive 800 mm.

The area considered suitable for rain-fed agriculture is located in the zone between 300 and 800 mm. This zone extends over the Darfur, Kordofan, Blue Nile and Kassala provinces with an area of 500 000–600 000 km^2.

Surface waters covers 130 000 km^2 of Sudan. Although the average Nile discharge at Aswan is 84 km^3, Sudan is allowed to use only 20.3 km^3 according to the Nile water agreement with Egypt (1959). For the 18 000 km^2 at present under irrigation, 18 km^3 of surface water is used.

The Jonglei project will make available for Sudan another 4.8 km^3 which the country can very well use for its ambitious land reclamation schemes. The problem is how much fertile soils can be put in production by optimizing the water economy.

The only other river system of significance separated from the Nile is the Wadi Azum, draining the western slopes of Darfur, receiving 600–1000 mm rain. The yearly volume of 0.200 km^3 could be made available for irrigation. Studies covering 1000 km^3 of eventually suitable soils are underway.

So far, no salinity or alkalinity hazards have affected the irrigated area, although long-term changes in salinity and alkalinity at the Gezira Research Station were recorded.

Groundwater resources

Large groundwater reserves are available in the Nubian Sandstone aquifers,

which however receive modest amounts of recharge, characterizing these waters as mainly non-renewable. Only in the area along the Nile, between Dongola and Wadi Halfa, due to infiltration of the Nile and Lake Nasser into the banks, a considerable area of renewable groundwater will become available.

Non-renewable resources: modest amounts of chromium, gypsum and manganese.

References: ALECSO (1977).

Syria (Syrian Arab Republic)

Area: 185 180 km^2
Cultivable land: 88 000 km^2
Rain-fed cultivated area: 55 000 km^2
Irrigated area: about 6000 km^2 being increased to 10 000 km^2
Forests: 4770 km^2
Steppe, semi-arid and arid areas: 92 300 km^2
Length of coastline: 300 km
Population in 1973: 6 827 800
Growth rate 1970–73: 3.3 per cent
Population in 1977: about 7 500 000
Urban population: 40 per cent
Rural population: 60 per cent
Nomad population: 4–6 per cent

Average annual precipitation distribution

Precipitation, also in the form of snow, changes abruptly from the coastal front towards the interior through the presence of coastal mountain ranges, which constitute a barrier for the wet westerly winds. The coastal mountain ranges with peaks exceeding 1500 m, receive 800–1500 mm. At the leeside of the mountains Quneitra in the south-west receives 350 mm; near Damascus the rainfall drops to 200 mm; Homs gets 450 mm; this drops to 350 mm in the Hama and Aleppo regions. The rift valley of the Ghab between the Al Nureirieh and Zawyeh mountains receives 600–800 mm. The large eastern part of the country receives less than 300 mm of which the major part receives less than 200 mm or even 150 mm, while 20 per cent of the total area located in the south-east has less than 100 mm of rainfall.

Rangelands

It is in the east that the arid and semi-arid area is situated which provides the vast extension of rangelands for the country's livestock: 6 000 000 sheep, 750 000 goats, 13 000 camels and 500 000 cattle. Seventy per cent of the feed comes from the rangelands and fallow crop lands forming 40 per cent of the rainfed zone with rainfall between 250 and 200 mm.

Increasing human and animal populations in recent years have created heavy pressures on the rangelands, causing over-grazing where water for livestock is present. This has been aggravated by the extension of dry farming in the most productive parts of the rangelands, reducing the grazing areas. Syria has an ambitious programme for integration of livestock into the farming system, by replacing the traditional fallow associated with crop production by introducing nitrogen forage legumes. This could play an important role in increasing fodder supplies to support livestock production and reduce rangeland grazing pressures, which create soil erosion by wind and water.

Milk is accepted as a major product of sheep.

Surface waters provide 32 km^3/annum, of which the Euphrates alone supplies 26 km^3/annum.

Surface water storage capacity

The Tabqa dam has a capacity of 11.9 km^3 and surface of 630 km^2. All other major and smaller dams may provide 1.1 km^3, bringing the total capacity to about 13 km^3.

Groundwater production is 1600 km^3 through a number (about 30 000) of pumped wells, mainly in the Damascus basin, the Orontes basin and the Aleppo basin. The quality is good to fair.

In the eastern part of the country salinity is becoming a major problem.

Many large springs can be found in the periphery of the limestone mountains draining a major part of their snowmelt or rain waters through fissures and joints towards the karstic systems, feeding the springs with yields of more than 1 m^3/sec.

Actual water use
- Agriculture: 6.000 km^3
- Domestic: 0.400 km^3

Future demand
- Agriculture 18.000 km^3
- Domestic: 1.500 km^3

The inadequacy of the water law has been recognized.

Petroleum production is just to satisfy the larger part of the interior needs.

References: ALECSO (1977), Economic Commission for Western Asia (1976).

Tunisia (Republic of Tunisia)

Area: 164 150 km^2 of which about 50 per cent can be used. The remaining part consists of the Sahara, rocky mountains and sebkhas
Cultivated area: 47 749 km^2
Rangelands: 20 000–33 000 km^2
Forest: 3600 km^2

Irrigated area: is more than 1000 km^2 is being extended to 2000 km^2
Length of coast: 1300 km
Population in 1973: 5 497 224
Growth rate: 2.4 per cent
Population in 1977: *c* 6 000 000
Half of the population is in rural areas

Average annual rainfall distribution

From 1000 mm in the north to 80 mm in the south, the Tel continuing from Algeria to Cape Bon receives 400–600 mm. The Steppe in the west, south of the Tell receives 150–300 mm and the coastal zone from 500 mm in the north to 200 mm in the south.

Surface water

The useful part amounts to 2.5 km^3/annum of which the Medjerda (and Mellègue) supply 1 km^3 with salt concentration varying from 1 to 3 g/l or 1000–3000 ppm. About 2 km^3/annum get lost into the sebkhas or towards the sea. In the mountainous steppe area with rainfall from 150 to 300 mm, 37 500 small dams have been made from 1968 to 1976. This was done to prevent storm run-off waters carrying away the already scarce soil cover. Runoff waters accumulated and infiltrated behind these dams force the heavy sediment load to be deposited and so form a kind of terrace behind these dams. In this way 125 km^2 of new land was added to the cultivable part of the country.

The surface discharge reacts of course on the irregular rainfall supply. As an example, Wadi Zeroud discharged in the hydrological season 1969–70, 2.5 km^3 while the average discharge is 0.060 km^3.

Groundwater production amounts to about 1.4 km^3/annum while in future 1.8 km^3 will be made available.

About 100 000 km^2 of Tunisia is threatened by desert encroachment, against which the government takes serious action: afforestation, sand-dune fixation and rangeland management. In the north 60 km^2 forest is planted per year. The total afforested cover exceeds 300 km^2. In the south, the oases are protected against wind-blown sand by earthen barriers covered by palm leaves and concentrate plates. Vegetation zones 50 m wide are planted between the barrier and the oasis, drawing their water from the water table till 7–8 m deep.

Salinity and alkalinity form serious problems.

Petroleum production started about 1972 (in 1975 production was 4 600 000 tonnes). Other non-renewable sources: phosphate, iron, lead and zinc.

Tunisia forms the eastern end of the Atlas ranges which continue without interruption from Algeria into Tunisia. The mountain tops reach nearly 1500 m. These mountains dip away under large coastal flats with sebkhas in the west, except at Cape Bon where they form a protrusion into the sea.

References: UNESCO (1976).

United Arab Emirates (UAE)

	Surface area (km^2)	Inhabitants
Abu Dhabi	67 250	125 000
Dubai	3 900	
Shargah	2 600	
Ajman	250	
Um al Qaiwan	750	
Ras al Khaimah	1 700	
Fujairah	1 150	
Total area	77 600	208 000 (1973)

Growth rate: 2.7 per cent
Agricultural area: 150 km^2
Irrigated area: 40 km^2
Length of sea coast of the mainland: 250 km including the coast of the isles, 6000 km.

Average annual rainfall

Rain falls mostly in December and January and is 65 mm
Surface waters vary from 0.160 to 0.270 km^3/annum
Groundwater production: 0.270 km^3/annum
Desalinated water production: $2 \times 10^6 m^3$/annum or 0.002 km^3
Present water use
- Agriculture: 0.331 km^3
- Domestic and industrial purposes: 0.031 km^3

Actual water needed
- Agriculture: 0.400 km^3
- Domestic and industrial purposes: 0.042 km^3

Petroleum production started in 1962.
Other non-renewable resources: asbestos, chromium, copper, iron and nickel.
References: Economic Commission for Western Asia (1976), UNESCO (1976).

Yemen (North) (Arab Republic of Yemen)

Area: 195 000 km^2
Permanently cultivated area: 15 000 km^2
Area cultivated once in four or five years depending on the rain: 10 000 km^2
Forest and bushes: 15 000 km^2
Irrigated area in 1971: 5800 km^2
Length of Red Sea coast: 600 km

Population in 1975: 6 400 000
Registered inhabitants: 4 519 000
Capital: Sanaa (population, 130 000)
Growth rate: 1.5 per cent
High emigration rate
95 per cent of the population in rural areas

Average annual precipitation

Coastal plains: 200 mm; on mountains as high as 3700 m, 1000 mm.

Uncontrollable floods such as the one in 1975 make soil conservation through flood control a high priority.

Non-renewable resources: saltpetre, gypsum and some copper and iron.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

Yemen (South) (People's Democratic Republic of Yemen)

Area: 297 683 km^2
Irrigated area: 1300 km^2
On surface and groundwater: 1030 km^2
On groundwater only: 265 km^2
The irrigated area can be expanded to a maximum: 2500 km^2
Length of sea coast: 1400 km
Population in 1977: 17 million
Growth rate 1970–73: 2.7 per cent

Annual precipitation

Rainfall varies between 0 and 100 mm in the coast strips and desert to above 350 mm/annum in the highlands, the catchment areas of the wadis.

Mean daily temperature from 15 to 38°C, minimum in January is 4°C, maximum in July is 48°C.

Humidity varies from 50 to 70 per cent.

Windspeed is up to 6 m/sec particularly during the monsoon.

Ten complete meteorological stations are being installed in the different agricultural areas in addition to the present ones. Evaporation (gauged by Penman Evaporation Pan) varies from 2.5 to 4 m/annum.

Surface water (and shallow groundwater): floods are intensive and of short duration, lasting at most a few hours and sometimes reach the sea or the desert. The main agricultural areas are located on the Quaternary wadi deltas of the wadis Tiban, Bana, Hassan, Ahwas, Maifaa, Haji and Masilah.

Total surface water supply is about 1.5 km^3/annum.

Wadi Tiban, on which Aden and the surrounding areas depend, discharged in the years 1973 and 1974 about 0.060 km^3/annum. While the Aden water supply

(0.022 m^3/annum) and irrigation of 30 km^2 on the basis of shallow wells require 0.033 km^3/annum. These two years including 1976 were dry years. The surface irrigation (floods and rains) were just over half the irrigated area of average water years. Less recharge and shallow groundwater withdrawal for irrigation caused a decline of the water table, especially in the middle delta, of some 10 cm/month combined with an increase in salt content. Sea-water encroachment occurred in the coastal strips.

Groundwater: There are some 5800 open wells and 600 tube wells. Groundwater production was 0.350 km^3/annum. With open wells problems and hazards are quite frequent. Open wells for agricultural purposes provide irrigation water to areas from less than 1 to 5 ha. The highest yields occur in the delta deposits of Wadi Hadramout (2100 open wells with average yield of about 61/s/well or 21 m^3/hr/well). These open wells will be replaced by drilled wells.

The most promising aquifer seems to be the Mukalla Cretaceous sandstone aquifer with thickness between 100 and 250 m, 30 wells reaching some 300 m deep tap this aquifer. About 35 ha/well have been reclaimed. The aquifer characteristics are under examination. Groundwater quality is generally good.

Since rains and floods are erratic, the general policy is to turn to deep drilling for permanent irrigation. Exploratory wells are being drilled to tap deeper aquifers and close off the unconfined aquifers at a depth of 120 m.

The drilling section in the Department of Irrigation executes yearly as its programme the reclamation of 14 km^2 of virgin land with the help of 70 drilled wells. The first three years of the five-year plan proved to be successful.

References: Economic Commission for Western Asia (1976), UNESCO (1976).

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